International Journal of

# Satellite Communications

July–September 1985
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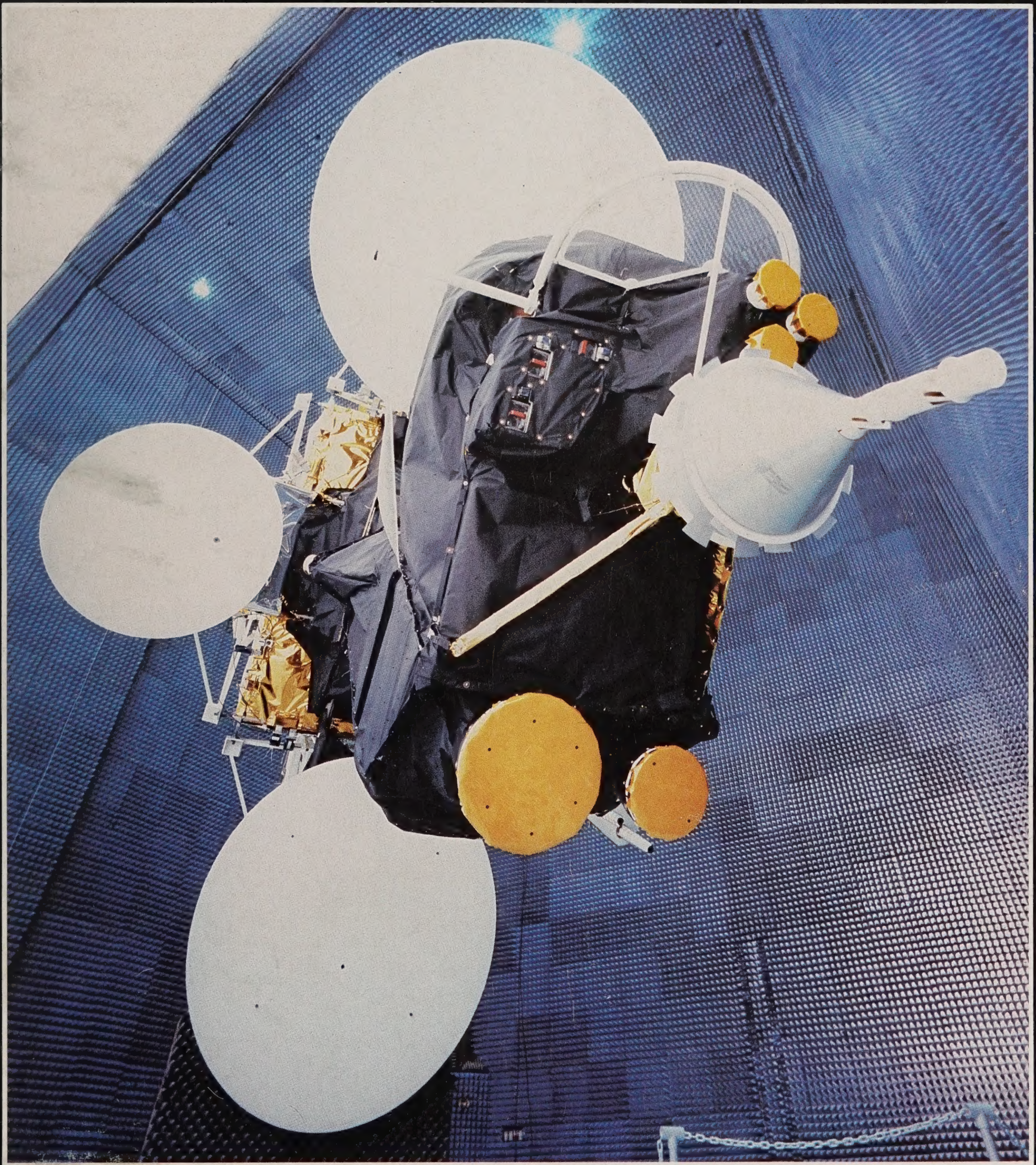

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International Journal of
# Satellite Communications



## AIMS

To publish initially a quarterly technical journal which acts as a focus for workers, as well as other parties interested in satellite communications. The journal spans the various disciplines applicable in the field of satellite systems and will provide rapid communication of new results and trends in this expanding area. As well as new research and development results in applications, the journal also invites general interest articles of a review or tutorial nature.

## RANGE OF TOPICS

The journal covers all aspects of the theory and practice of satellite systems and networks, e.g. telecommunications, remote sensing, data collection and broadcasting. Topics include:

Network Philosophy and Planning

Communication Systems and Equipment

Antennas: Earth Station and Satellite

Space Craft Technology and Control

Earth Station Equipment and Planning

Propagation Aspects including Interference and Co-ordination

Applications of Satellite Systems

User Aspects e.g. Marketing

Regulatory Matters etc.





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# EDITORIAL

## SATELLITES—EUROPE

In reviewing the current satellite scene in Europe, events have been overshadowed by the launch failure of Ariane V15 carrying the ECS-3 and SPACENET 3 satellites. This represents the first commercial launch failure of the Ariane rocket after nine successful launches.

With total outstanding insurance claims of around $250 million, once again the insurance market has been thrown into disarray with rumours of future increases in coverage exceeding the 25 per cent rate and even suggestions of the insured party sharing the risk. If Arianespace are to preserve the edge over the shuttle they will need to rapidly locate and rectify the cause of the third stage failure and publish a revised launch programme. Meanwhile, EUTELSAT, whose definitive status came into effect on the 1st September with 26 member states, are planning to bring forward the launch of ECS-4 to the earliest possible date. ECS-3 was intended to carry only national TV channels and its loss causes problems for the rapidly booming TV distribution market in Europe.

Although the TV distribution networks and cable systems seem to be taking off well, the DBS scene in Europe is still very confused. In the U.K., forces are still regrouping after the collapse of the group of 25 and the demise of UNISAT. It is generally considered that the IBA will go ahead with some sort of initiative for a medium power satellite, after the announcement of an open competition for the space segment by the U.K. government. In France the future of TDF-1, due for launch next year, remains uncertain due both to the lack of users and to political pressures to delay the project. Meanwhile, French commercial TV interests are showing interest in the lease of capacity on the TELECOM 1 system, where 20 W transponders will allow quasi-DBS operations to terminals of around the 1 m size. In West Germany the situation is remarkably similar with TV-SAT (launch planned for 1986) suffering from lack of programming support, whilst the growing cable markets are making heavy use of EUTELSAT satellites. The Irish have made a decision in principle to go ahead with DBS and are negotiating with Atlantic Satellites for a DBS satellite to be launched into the 31°W slot around 1988. Considerable interest in the latter is being shown due to convenience of this orbit slot for North Atlantic traffic. In Luxembourg the S.E.S. project is making good progress and about to sign with RCA for two DBS satellites for launch in the next two years.

The European space agency (ESA) has recently gone public on their programme of research and development. The latter is concerned with advanced satellite research for the small fixed service and for the mobile (Maritime/Aeronautical/Land) services. R and D on the necessary components to incorporate multiple beam antennas, on-board processing (see paper by Evans) and intersatellite links is under way. Experimental packages are due to be flown on a shared cost basis with operational satellites around the 1990/1991 time frame, and will be followed up with a complete pre-operational satellite around 1995. In addition an experimental satellite, OLYMPUS, will be flown in 1987/1988 to use the 20/30 GHz bands for experimental purposes. This satellite also contains an SS-TDMA 12/14 GHz package.

In the U.K. the long awaited announcement of the British National Space Centre is about to be made. Rumours are that the new space centre (Agency) will be located in London and Farnborough and will coordinate U.K. satellite and space work. In the university sector a consortium are working on the follow-on from CERS (see paper by Evans) now called T-SAT. The satellite is to be placed in a highly elliptic, molniya, orbit and besides a mobile communications package will fly a whole range of new U.K. space technology.

The European satellite scene, despite a few set-backs is alive and equiping itself for the future markets.

B. G. Evans

# INAUGURAL LECTURE

**Professor B. G. Evans:**
This paper is the inaugural lecture of one of our co-editors Professor Barry Evans, which he presented at the University of Surrey on the 6th March 1985. In his opening address, the Vice-Chancellor Dr. A. Kelly introduced Professor Evans as follows:-

'Barry Evans received a first class honours degree in Electrical Engineering and Ph.D. from the University of Leeds in 1965 and 1968 respectively. His graduate work has been in microwave circuits and antennas but on leaving Leeds and taking up a British Telecom lectureship at the University of Essex he started his move into communications.

At Essex he was responsible for setting up teaching in Telecommunications Systems as well as research in radio and satellite communications. His group there became internationally known and was responsible for the introduction of companded f.m. single channel for carrier satellite communications as well as major advances in the theory and practice of dual polarization frequency reuse. He became a senior lecturer and reader in Telecommunications in 1975 and 1978 respectively. He has consulted world wide in the area of satellite communications and sits on major national and international committees in his subject areas.

In 1983 he was appointed to the Alec Harley-Reeves Chair in Information Systems Engineering at the University of Surrey. At Surrey he leads the Satellite and Telecommunications research groups with major research programmes in on-board satellite processing and spacecraft engineering'.

# TOWARDS THE INTELLIGENT BIRD

'A bird of the air shall carry the voice,
and that which hath wings
shall tell the matter'
*Ecclesiastes*

## THE BIRTH AND THE CHALLENGE

Satellite communications began in 1945 with the prediction by the, now famous, science fiction author Arthur C. Clarke that three satellites in geostationary orbit (Figure 1), that is at a distance of 36,000 km above the equator where to an observer on the earth's surface they remain approximately stationary, could provide world-wide telecommunications coverage. This was no crystal-ball gazer's prophecy, as Clarke had realized that a rocket only several times larger than the V2's that he had experienced with such horror in the Second World War could in fact launch such a satellite. This, coupled with the realization that the innovations in microwave technology needed for the installation of radars could also be used to produce the communications equipment necessary for transmission to, and from, such satellites, made Clarke's prophecy no more than an educated forecast in telecommunications. However, Clarke produced the concept of the 'sky-hook' on which to hang our satellites. Since the early experimentation and trials via metallized meteorological balloons (the 'Echo' programme) and subsynchronous satellites (the subsynchronous era) we have passed through, or are about to enter, five eras of satellite communications (as illustrated in Table I). I would like to consider the driving force behind this rapid evolutionary path; it has in fact been society's insatiable demand for more and more communications. More and more telephone (voice) circuits and increased video (broadcast) circuits have been the classical traffic patterns. Nowadays, these have been joined by the demand for more and more data services of all kinds: computer-to-computer services, electronic mail and electronic funds transfer, plus a range of new video services such as facsimile, videoconferencing, slow-scan television and many others, too numerous to

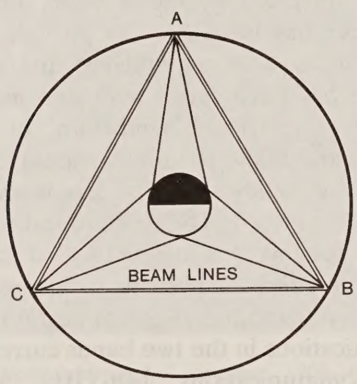


Figure 1. Arthur Clarke's view of a three-satellite geosynchronous global communications system

Table I. Satellite communications eras

| | |
|---|---|
| 1. Subsynchronous era | 1958–1963 |
| 2. Global-synchronous era | 1964–1972 |
| 3. Domestic and regional era | 1973–1981 |
| 4. Small station application era | 1982–1990 |
| (i) broadcasting | |
| (ii) business | |
| (iii) mobile | |
| 5. Intelligent satellite era | 1990 → |

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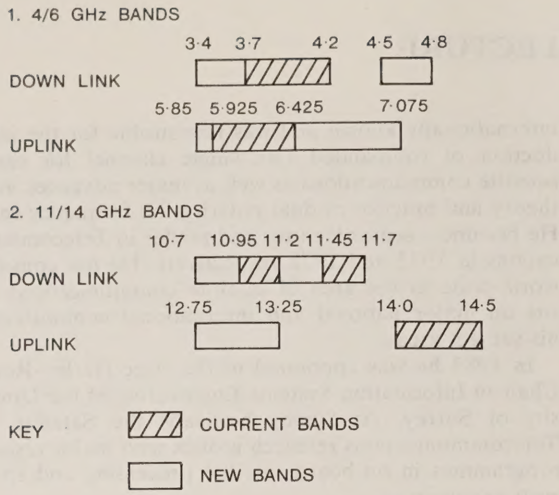



Figure 2. Frequency bands 4/6 GHz and 11–12/14 GHz as allocated to satellite communications by the ITU

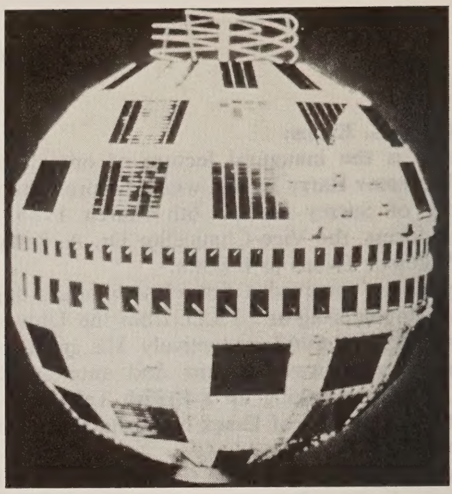


Figure 3. TELSTAR: subsynchronous satellite launched in 1962

mention. It must be pointed out that besides the civil communications requirements there have been other driving forces in the fields of military communications, especially in surveillance and in earth-resource sensing. I will restrict myself here to the civil communications field as perhaps, unlike other areas of technological advance, this has dominated satellite communications.

The problem faced by the satellite communications engineer has been how to provide for such traffic and services in an efficient and economic manner. He has been faced with one major constraint, that of restricted bandwidth. In order to avert chaos, and allow for international communications, the frequency spectrum has been planned (by the International Telecommunication Union (ITU)) and various portions allocated largely to separate communication systems or means of communication. An example of the allocation to satellite communications in the two bands currently used in civil communications (4/6 GHz and 11–12/14 GHz) is shown in Figure 2. It will be seen that even with recent additions, there is precious little bandwidth into which to cram our communications requirements. So it is this, more than anything else, that has called for technological innovation and has presented satellite engineers with their challenge.

## THE EVOLUTION (OR REVOLUTION) OF SATELLITE COMMUNICATIONS

I would like to demonstrate how rapid the evolution has been and describe some of the innovations in the global and regional/domestic eras.

Let us start, however, with an early satellite from the subsynchronous era. The subject was at such an early stage in its development, and perhaps still glamorous enough for the satellites to be given names. TELSTAR (Figure 3), launched in 1962, is certainly my own, and perhaps many reader's, first recollection of satellite communications. I remember with admiration seeing the first transatlantic television pictures being relayed by this subsynchronous satellite on its thirty minute path over the U.K. It was in fact in 1964 that the first communications satellite, Early Bird (Figure 4), was launched into geostationary orbit, and this was followed shortly after by the formation of the first international organization to operate 'global' satellites: INTELSAT. They still today launch and operate the satellites above the major oceans that provide us with world-wide communications. They have, via a programme of research and development, produced a range of satellites to meet international traffic demands. INTELSAT'S I and II (1967) were small satellites providing capacity for only 240 telephone channels or one television channel between earth-stations in the Atlantic global coverage region (Figure 5). The satellites were spun in orbit to achieve stability, and so the fixed-pointed antennas wasted a great deal of energy into space. However, some important new concepts were proven, for example the technique of multiple-access, which allowed many earth-stations to intercommunicate simultaneously by frequency division through the one satellite. These initial

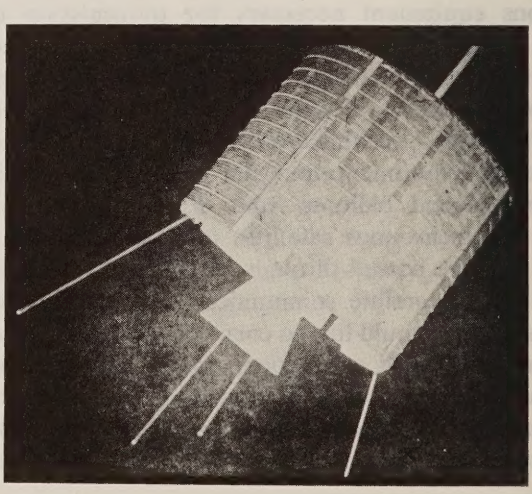


Figure 4. Early Bird satellite launched in 1964 (courtesy INTELSAT)

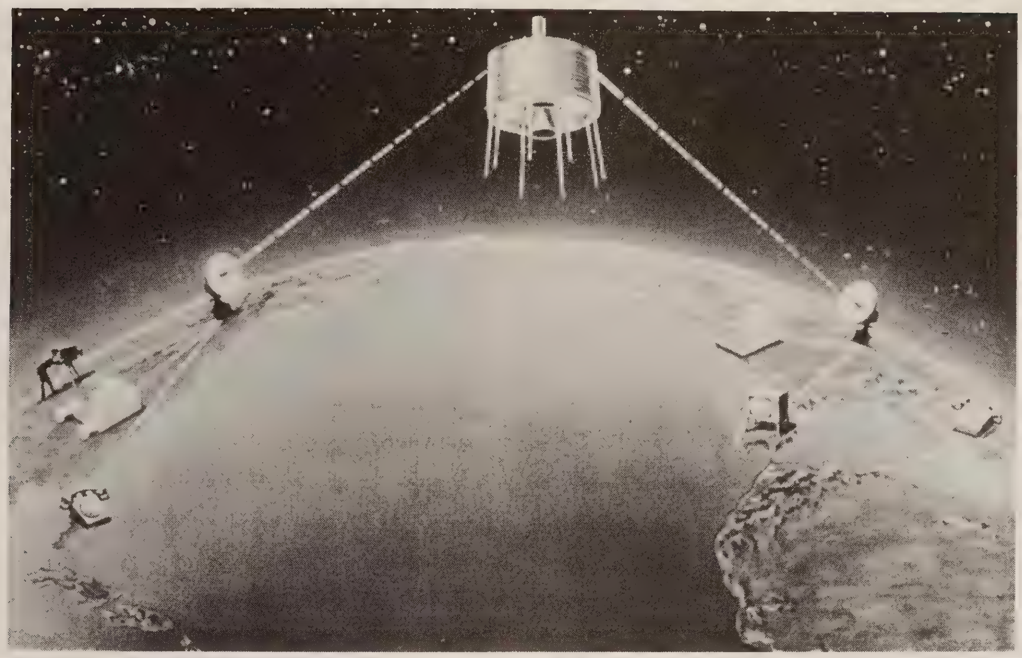


Figure 5. Atlantic global coverage with INTELSAT I-II satellite

satellites were soon saturated with the increase in traffic demands, precipitated by the demonstration that the need would indeed be satisfied, and a new and larger satellite, INTELSAT III (Figure 6), was launched in 1968. The reason for the larger satellite is to increase the surface area on which may be mounted the solar-cells which generate the primary electric power that runs, amongst other things, the communications payload. More power to the payload translates to greater radiated radio frequency power from the antennas, which in turn translates to the ability to transmit more traffic, in this case increasing the capacity to 1500 circuits plus 4 TV channels. Thus the bigger the satellite, the greater the traffic carrying capacity. With the INTELSAT III satellite, the antennas were de-spun so that they continuously pointed to the surface of the earth and energy was not wasted into space. In 1968 one of these satellites was in position above each of the major oceans, Atlantic, Pacific and Indian and Arthur Clarke's prophecy (Figure 7) had become a reality only 23 years after it had first been made.

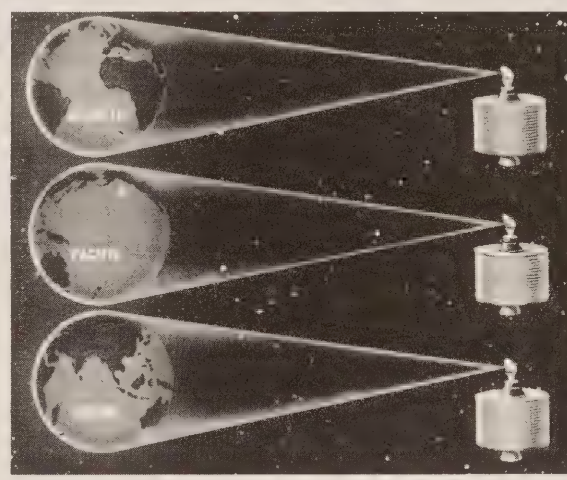


Figure 7. World-wide global coverage, 1968, via INTELSAT III satellites

Commensurate developments and innovations had also been taking place in earth-stations; large (30 m diameter) 'gateway' earth-stations, such as that at Goonhilly Downs in the U.K. (shown in Figure 8), had been established in most of the developed countries. These acted as a focus through which the intercontinental traffic was routed from the various terrestrial telecommunications networks.

Amazingly, international traffic demands were still increasing at rates of around 25 per cent per annum, as seen in Figure 9, and no signs of the saturation on the now-classic logistic curve were in sight. The bigger satellite approach produces diminishing returns and higher launch costs, and so the next INTELSAT satellite IV (Figure 10), launched in 1971, although larger, also needed the new concept of spot-beam coverage to increase capacity.

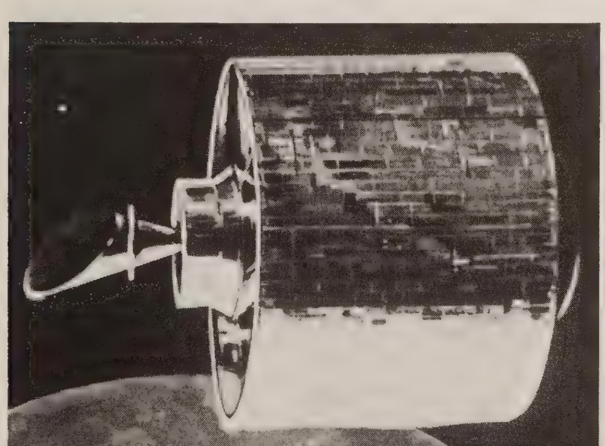


Figure 6. INTELSAT III satellite launched in 1967 (courtesy INTELSAT)

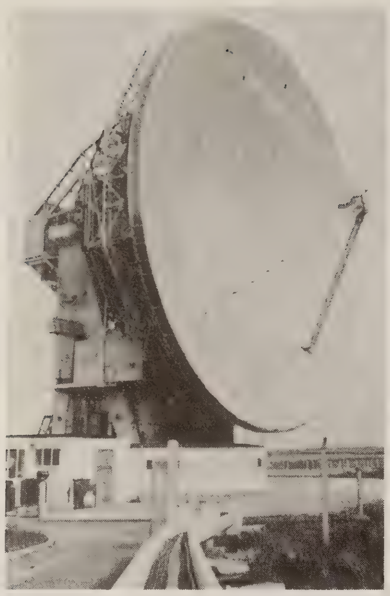


Figure 8. Thirty metre diameter INTELSAT Standard A gateway earth-station at Goonhilly Downs in the U.K., 1968 (courtesy BTI)

This concept, which is illustrated in Figure 11, allows the valuable satellite power to be concentrated on the traffic-generating land-masses and avoids wastage in the oceans. ('The end of the "fish-warmer" stage'!) The INTELSAT IV and IVA satellites were considerable advances on the first-generation satellites, weighing 10 times as much and carrying 4000–6000 telephone channels plus 2 video channels, in 12–20 transponders, respectively.

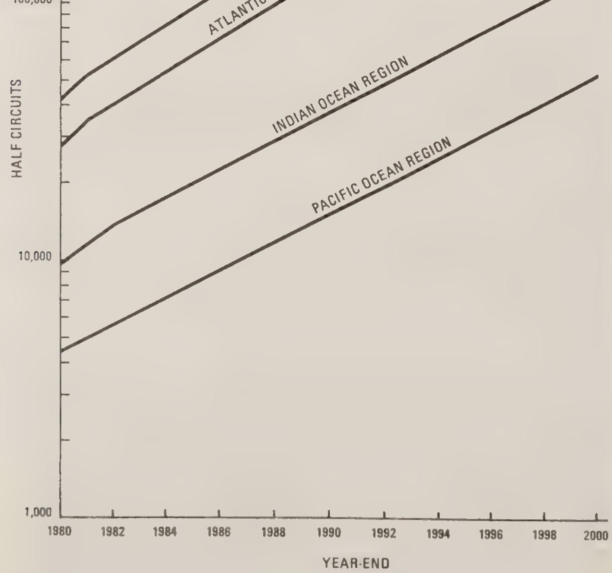



Figure 9. INTELSAT global traffic predictions (courtesy INTELSAT)

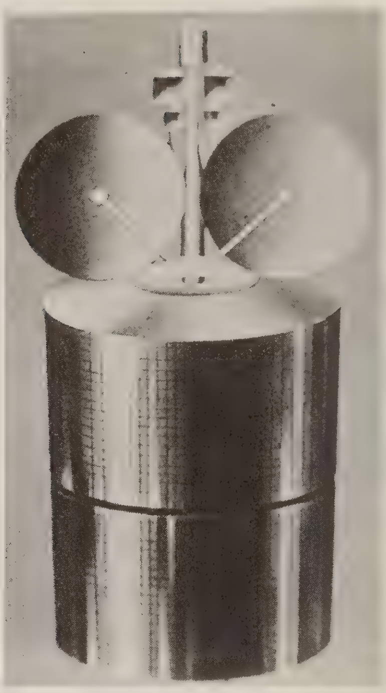


Figure 10. INTELSAT IV satellite launched in 1971 (courtesy INTELSAT)

The next major innovation appeared on the INTELSAT V (Figure 12) satellite (1980) which followed close on to the IVA version. This was the concept of frequency reuse, both by spatial separation and by the use of orthogonal polarizations. This necessitated shaped-beam antennas, carefully contoured to follow the land masses and involving hundreds of phased primary horn radiators. As shown in Figure 13 a fourfold frequency reuse could be accomplished via the use of orthogonal polarizations on the zonal and hemispherical beams. The INTELSAT V satellite also used the new 11/14 GHz frequency bands for the first time in the spot beams. Thus, a somewhat revolutionary satellite, incorporating several new innovations, was launched; it weighed approximately 2000 kg, was the size of a London bus and had a telecommunications capacity of 12,000 telephone channels and 2 video channels. The rapid evolution of satellites is seen in Figure 14, which clearly shows the dramatic strides made

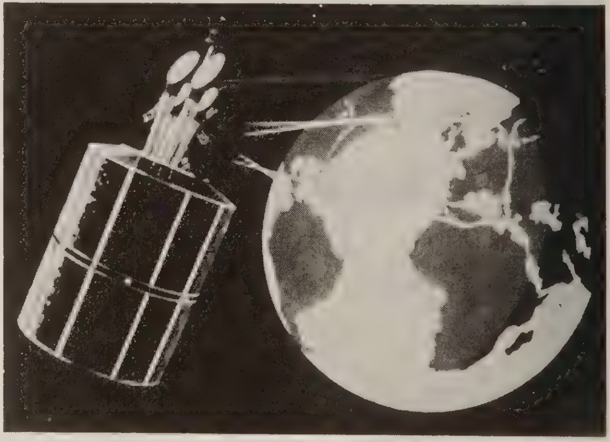


Figure 11. Shaped-beam coverage of the Atlantic region

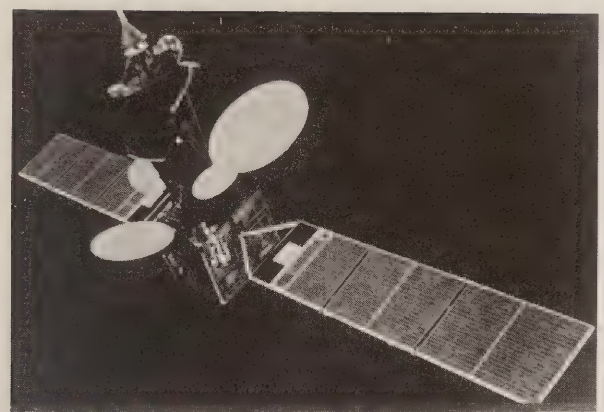


Figure 12. INTELSAT V satellite launched in 1980 (courtesy INTELSAT)

in such a short time span. The INTELSAT V satellites carry today's transoceanic communications and, from humble beginnings, the INTELSAT global system has grown to include today a network of 15 satellites in orbit, more than 650 earth-stations, linking more than 165 countries. The modern 30 m 'gateway' earth-stations look somewhat different to the early Goonhilly I antenna, as seen in Figure 15, which shows a modern INTELSAT Standard A earth-station located in Ras-Al-Kaimah, incorporating a beam-waveguide feed and much slimmed down backing and tracking structure.

The preceding remarks refer mainly to the global era, which still provides us with an International connection today. In the mid 1970s, however, satellite communications became an attractive proposition for national and regional systems. This was particularly true of countries and regions which included mountainous and inhospitable terrain over which it was impossible to provide telecommunications economically in any other way. It was also ideal for isolated and thinly spread communities. Canada in 1972 via the ANIK series of satellites, and the Indonesian islands via the PALAPA satellites from 1976, were examples of countries and regions for which separate satellite systems have been installed. Many countries could

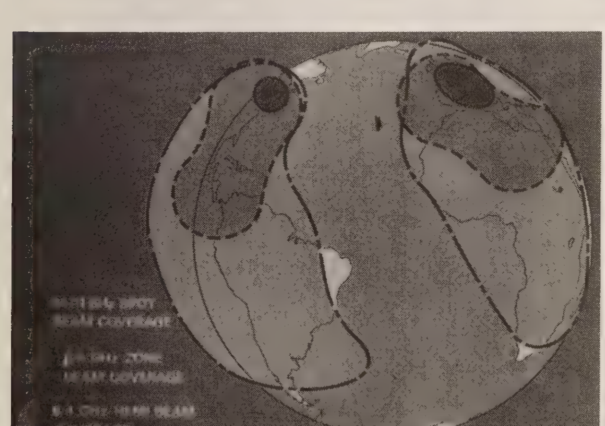



Figure 13. Shaped-beam coverage of Atlantic region on INTELSAT V showing spatial and orthogonal polarization frequency reuse in hemi and zonal beams (4/6 GHz) and 11/14 GHz use in spot beams

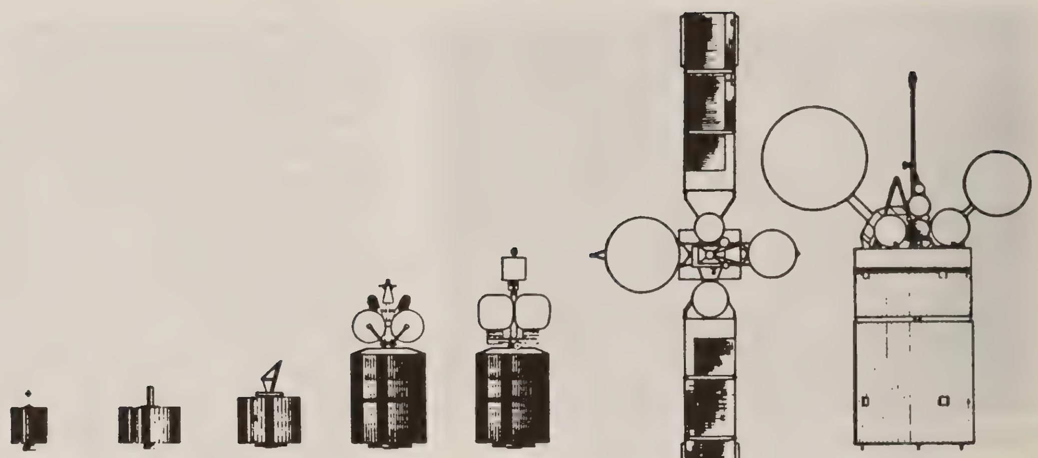
not afford their own satellites, and so INTELSAT instituted a policy of leasing bandwidth on spare global satellites. To date, 54 countries with in excess of 700 antennas are operating domestic and regional systems of this kind. The antennas used for this purpose (Figure 16) are much smaller (11–13 m in diameter), and much cheaper, (£$\frac{1}{2}$–1M as against several £10Ms for a 30 m antenna earth-station). The domestic era has enabled many developing countries to install a trunk telecommunications system in a very short period of time, e.g. 6–12 months, whereas via terrestrial means this would have taken years. Since it is a proven fact that the development of a telecommunications hierarchy is directly linked to national economic indicators, this has been an important step in the development of the economy of such countries.

Now, to date, and even with the latest INTELSAT VI satellite (Figure 17) due for launch in 1986, which is larger but contains no real innovations, all satellites discussed so far have been 'dumb'. That is to say they merely contain amplifiers and frequency changers (see Figure 18) and are in fact giant repeaters in the sky. We will see later that the succeeding eras are going to require very different satellites.

## TECHNOLOGICAL INNOVATIONS

Thus far mention has been made of several technological satellite innovations. I would like now to turn my attention to a few specific illustrative examples with which I have personally been associated.

I think that my colleagues in the business would be very surprised if I did not mention the problems of propagation of the radio waves to, and from, the satellites. The major problems occur with the passage of these waves through the ionosphere and the troposphere, and it is the latter with which I have been specifically concerned. I have already illustrated the effective increase in capacity that can be achieved by reusing the frequency on orthogonal polarizations. One major problem with this is the passage of the radio waves through the troposphere. If the latter contains precipitation particles it constitutes an anisotropic medium which produces coupling between the two polarization states, as illustrated in Figure 19. Raindrops, for instance, are not perfect spheres, but rather, oblate spheroids, and this produces differential amplitude and phase to the orthogonal polarization states. In addition, there is a spread of raindrop canting angles which, together with the latter, contribute to the depolarization. Small ice crystals existing high in the troposphere can also cause significant depolarization, particularly when higher frequencies are involved, and when the crystals are aligned, for instance by electric fields associated with thunderstorms. Quantification of these processes is needed if the system designer is to allow for them, or even



| INTELSAT DESIGNATION | I | II | III | IV | IV-A | V | V-A | VI |
|---|---|---|---|---|---|---|---|---|
| YEAR OF FIRST LAUNCH | 1965 | 1966 | 1968 | 1971 | 1975 | 1980 | 1983 | 1986 |
| PRIME CONTRACTOR | HUGHES | HUGHES | TRW | HUGHES | HUGHES | FORD AEROSPACE | FORD AEROSPACE | HUGHES |
| DIMENSIONS (Undeployed) | | | | | | | | |
| WIDTH, m. | 0.7 | 1.4 | 1.4 | 2.4 | 2.4 | 2.0 | 2.0 | 3.6 |
| HEIGHT, m. | 0.6 | 0.7 | 1.0 | 5.3 | 6.8 | 6.4 | 6.4 | 5.3 |
| LAUNCH VEHICLES | THOR DELTA | | | ATLAS CENTAUR | | ATLAS CENTAUR, OR ARIANE 1, 2 | | STS OR ARIANE 4 |
| SPACECRAFT TRANSFER ORBIT MASS, Kg. | 68 | 162 | 293 | 1,385 | 1,469 | 1,946 | 2,140 | 12,100/3,720 |
| COMMUNICATIONS PAYLOAD MASS, Kg. | 13 | 36 | 56 | 185 | 190 | 235 | 260 | 600 |
| POWER EOL EQUINOX, Watts | 40 | 75 | 134 | 460 | 600 | 1,270 | 1,270 | 2,200 |
| DESIGN LIFETIME, YEARS | 1.5 | 3 | 5 | 7 | 7 | 7 | 7 | 10 |
| RATED VOICE CHANNEL CAPACITY IN AOR | 480 | 480 | 2,400 | 8,000 | 12,000 | 25,000 | 30,000 | 80,000 |
| BANDWIDTH, MHz. | 50 | 130 | 300 | 500 | 800 | 2,300 | 2,180 | 3,680 |
| ANTENNA BEAM COVERAGES | | | | | | | | |
| C – BAND | TOROIDAL NORTHERN ONLY | TOROIDAL ALMOST FULL EARTH | DESPUN EARTH COVER | DESPUN EARTH COV. AND 2 SPOTS STEERABLE | DESPUN EARTH COV. AND 2 HEMI | 3 – AXIS EARTH COV., 2 HEMI, 2 ZONE | 3 – AXIS DUAL POL. EARTH COV., 2 HEMI, 2 ZONE 2 SPOTS | DESPUN DUAL POL. EARTH COV., 2 HEMI, 4 ZONE |
| Ku – BAND | N.A. | N.A. | N.A. | N.A. | N.A. | 2 SPOTS STEERABLE | 2 SPOTS STEERABLE | 2 SPOTS STEERABLE |
| L – BAND | N.A. | N.A. | N.A. | N.A. | N.A. | EARTH COV. | N.A. | N.A. |

Figure 14. The range of INTELSAT satellites I–VI (courtesy INTELSAT)

design equipment to remove any interference created by them.

In the 1970s this problem occupied a great deal of researchers' time, including my own. Firstly in the measurement of such effects and their statistical quantification. Figure 20 shows an event measured at 11 GHz which would be particularly severe to a communication system. Secondly, a theory had to be perfected to account for such phenomena, so that the cross-polarization could be predicted for

Figure 15. Modern 30 m Standard A INTELSAT earth-station in Ras-Al-Kaimah (courtesy C & W Ltd)

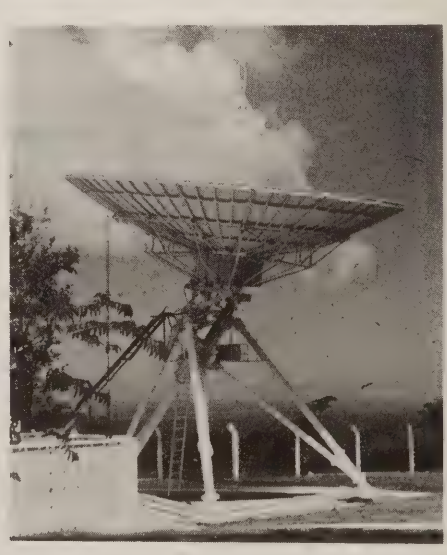


Figure 16. INTELSAT Standard B antenna (11–13 m) located in the Seychelles (courtesy C & W Ltd)

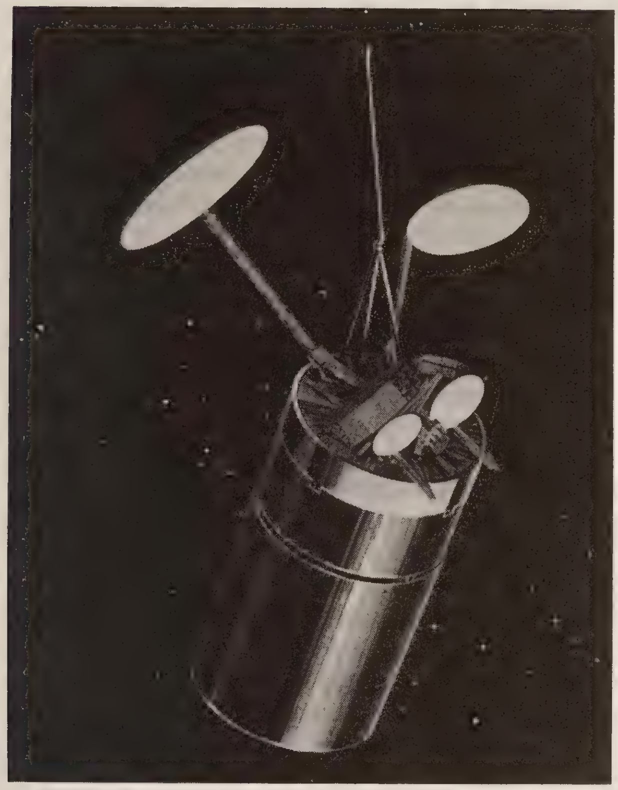


Figure 17. INTELSAT VI satellite due for launch in 1986 (courtesy INTELSAT)

new frequency bands and for various locations. Figure 21 demonstrates the success that we had in accomplishing this, but in so doing, glosses over the not inconsiderable electromagnetic scattering calculations and modelling that made it all possible. Finally the solution for particularly severe cases, was found in the cancellation of the crosstalk interference (Figure 22) by adaptively coupling some of the main copolar channel, appropriately changed in phase and amplitude, into the orthogonal channel. This was an ideal application for microprocessors, which were beginning to appear cheaply by the mid 1970s.

So to my second example of technological innovation, for which I return to the major traffic component in early satellite systems—'speech'. The demand was for very large numbers of telephone channels, which were still most effectively transmitted by analogue means in groups called frequency

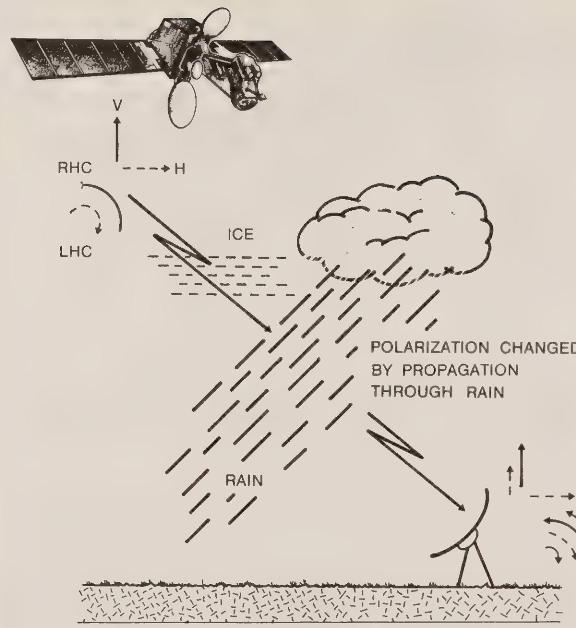



Figure 19. The propagation problem

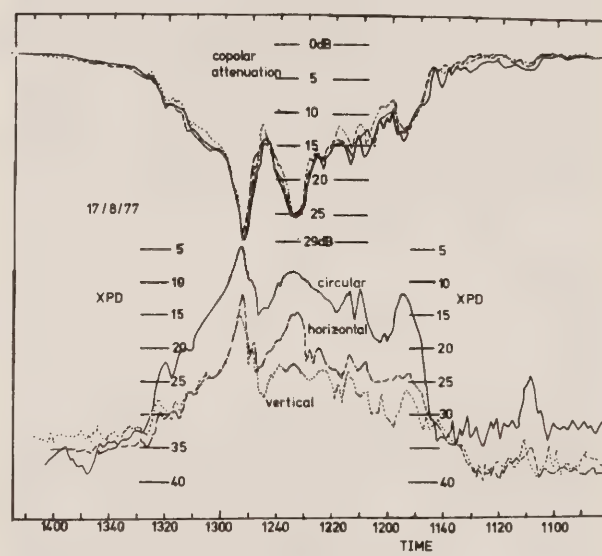



Figure 20. Attenuation and cross-polarization measured at 11 GHz in a bad storm

division multiplexes, modulated onto high capacity carriers using frequency modulation. With the introduction of the new domestic and regional satellite systems in the mid 1970s, developing countries

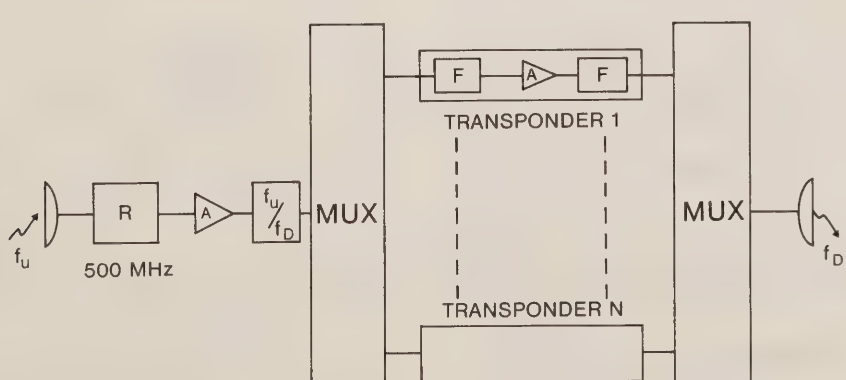



Figure 18. The 'dumb' satellite concept

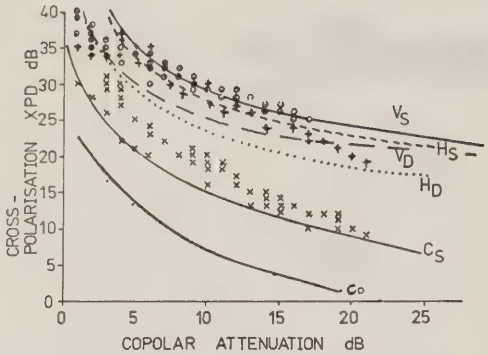



Figure 21. Comparison of measured and theoretically predicted cross-polarization at 11 GHz. Simultaneous linear/circular depolarization on 11.6 GHz, 18 km terrestrial path: S—stochastic model; D—deterministic model

did not require large groups of telephone channels, but merely a few, which could be expanded as and when needed. This gave birth to the idea of single-channel-per-carrier (SCPC) systems, in which each telephone channel was allocated to a unique carrier. The problem was then to reduce the bandwidth per speech channel and hence concentrate more channels into the restricted and expensive bandwidth resource. This is when I first became interested in speech communications and, together with my research group at the University of Essex, proposed, for the first time, the use of syllabic companders in a frequency modulation SCPC satellite system. The

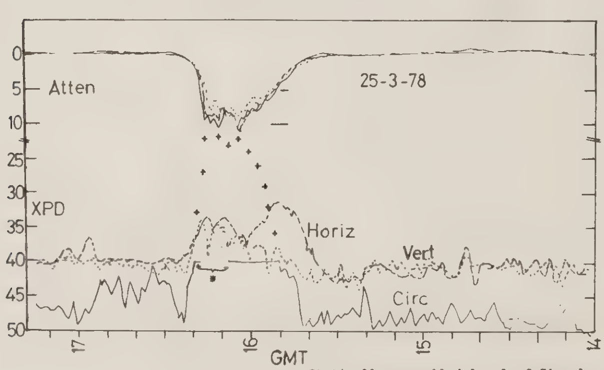



Figure 22. Adaptive cancellation of cross-polarization: + approximate theoretical XPD, from a stochastic model, using the recorded attenuation levels; * the cancellation system was set to adapt at 40 dB XPD. For the period marked '*' the introduced cancelling phase shift was not sufficient in range to fully cancel the XPD below 40 dB XPD, owing to the excess phase shift caused by the precipitation

idea had been prompted by the search for a cheap yet efficient satellite system for developing countries. Syllabic companders (see Figure 23) had been around for some time in terrestrial networks, and their operation basically compressed the speech volume range at the transmitter and expanded it at the receiver. When combined with frequency modulation, they not only allowed the bandwidth per speech channel to be reduced, but also gave a subjective quality advantage to the communication. We were able to demonstrate this by performing a series of subjective tests (Figure 24) and to show that quality standards could be met with the reduced bandwidth service. I am pleased to say that companded f.m. is today used in nearly all domestic satellite systems operated by developing countries, and also by the international maritime satellite communication system (INMARSAT) which operates communications world-wide to shipping.

On reflection it is interesting to note that this was probably the first use of 'processing' for speech in satellite systems. In common with terrestrial communication systems, satellite systems have moved from analogue to digital means of transmission. Current generation satellites are beginning to be used in time division multiple access (TDMA) mode

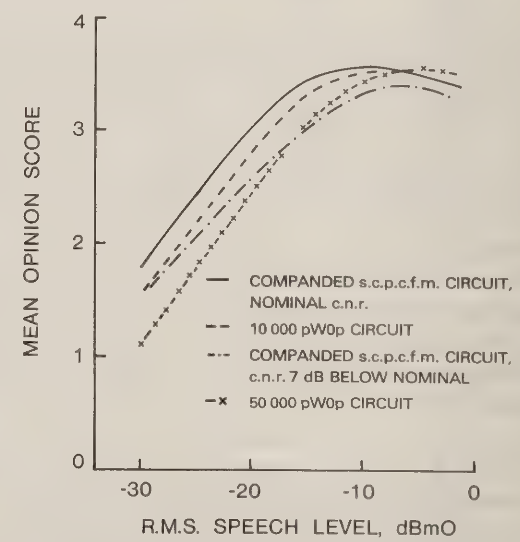



Figure 24. Subjective quality of SCPC companded frequency modulation

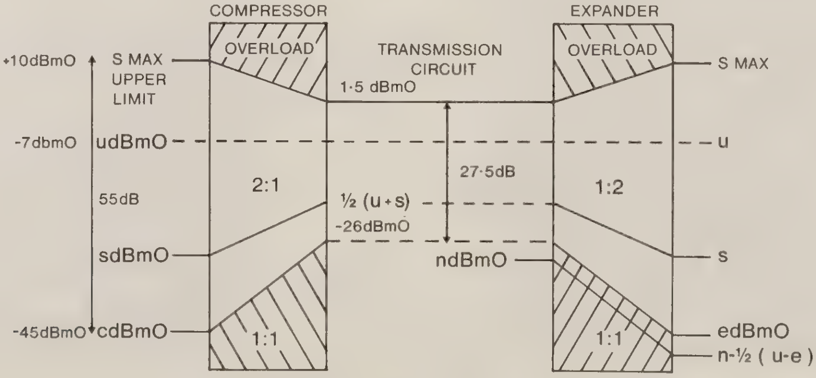



Figure 23. Operation of a syllabic compander

to transmit digitized traffic. This means that rather than users sharing the satellite resource by having different frequency carriers they are allocated different time slots, and communicate in bursts of information to the satellite, as illustrated in Figure 25. The result of this is that the traffic, particularly speech, which is an analogue signal must be digitized prior to transmission. Developments on the terrestrial network had led to a particular form of analogue-to-digital conversion called pulse code modulation (PCM) being adopted as a standard. PCM was in fact first proposed by the man whose name my Chair commemorates, Alec Harley Reeves, in 1937 as a conscious attempt to realize in the transmission of telephony, the noise immunity characteristic of telegraphy. The basic idea is demonstrated in Figure 26, where the analogue signal is first sampled, then quantized and finally coded for onward transmission. This technique is used today in the telephone network and is gradually superseding analogue techniques. The problem for satellite communications, however, is that it uses wide bandwidths, or high bit-rates in the digital world; 64 kb/s is the standard channel rate. We thus return to the problem of whether we can reduce the bandwidth (in digital terms, bit-rate) yet maintain the quality. The answer lies in 'processing' and brings me right up to the present time and to some of the research that is currently going on in my laboratory at Surrey. It is possible to introduce 'digital signal processing' into the analogue-to-digital process such as to trade-off the processing gain for reduced bit-rate and yet still to preserve the commercial quality of the speech. The first stage, DPCM, is to transmit only the difference between the current and a predicted future sample which is obtained from a suitably weighted mean of previous samples (a long-term predictor). If the latter is made adaptive to the short-term variations of the speech, by incorporating variable weightings, and a variable level quantizer included we have ADPCM (Figure 27), which improves the quality for a reduced bit-rate transmission. Such systems enable the transmission rate to be reduced to 32 kb/s, and we, along with other researchers in the field, have demonstrated in the past few years that

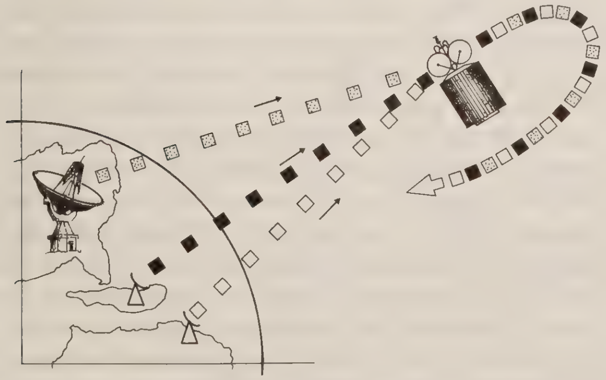


Figure 25. The burst mode operation in time division multiple access (TDMA)

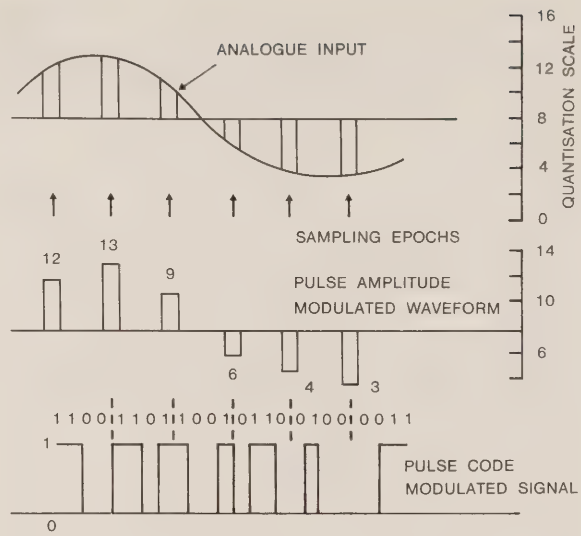



Figure 26. Basic principles of pulse code modulation (PCM)

32 kb/s systems can produce equivalent speech quality to 64 kb/s PCM. Such techniques have now been standardized and will start to be introduced into terrestrial and satellite communication systems in the near future. Meanwhile, we continue to look at further reductions in bit-rate and are currently looking at 16 kb/s techniques, for instance, with adaptive predictive coding (APC) (see Figure 27). This technique adds further processing stages, aimed at following the rapidly changing speech spectral envelope and producing a better quality. This is shown in Figure 27, where following a simple adaptive quantizer we have a short-term predictor which models the transfer function of the human vocal tract, together with a long-term predictor which represents the periodicity of the speech. These together allow us to maintain good speech quality even down to 16 kb/s. Ironically, we are now working on techniques which will replace the companded f.m. systems in maritime and domestic thin-route satellite systems that we invented in the early 1970s. Such is the pace of progress. The future is to look to even lower bit-rates of 9·6, 4·8 and then 2·4 kb/s. The latter have traditionally been the domain of the military, who have been satisfied with synthetic speech quality via vocoders rather than the high quality waveform coders of the commercial world. However, digital signal processing is becoming increasingly more powerful, cheaper and smaller in size. By reducing the bit-rate per speech channel it should become possible to satisfy the telephonic demands of society over the next decade, even within the bandwidth constraints imposed upon the design engineer today. Reduced bit-rate speech will have then solved the major bandwidth constraints for global, domestic and regional satellite systems.

## NEW MARKETS

Let me now return to the market-place of satellite communications as it is today. We have a well-

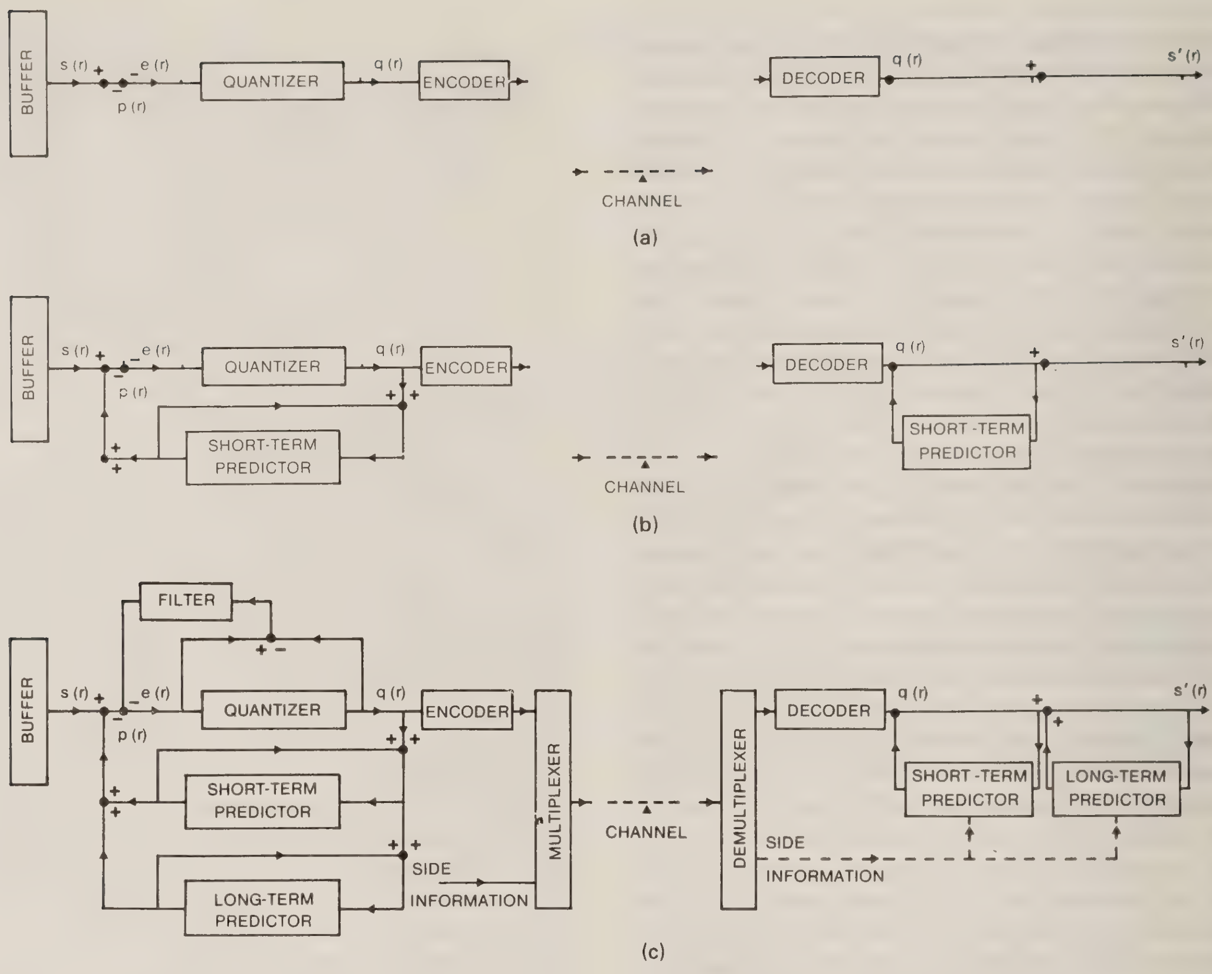



Figure 27. Signal processing for reduced bit-rate speech: (a) PCM; (b) ADPCM; (c) APC

developed international global system under INTELSAT together with a growing number of domestic and regional systems. Many of the new technologies that I have mentioned, and in particular the reduced-bit-rate speech, will enable such systems to adequately cope with traffic demands well into the 1990s. If one further considers the introduction of a transatlantic optical fibre system (TAT-8) in 1988 and the resulting increase in capacity one really starts to ask the question 'whither satellite sytems?'

I am convinced that we stand at a crossroads in the development of satellite communications, which is represented by my fourth era in Table I—the small dish/mobile era. These applications represent new markets to those traditional for our subject and will, in my opinion, require new solutions to new problems. Let us then look at the nature of these new markets. There are three new requirements which have already started to appear and are

(i) direct broadcasting of television
(ii) small dish business systems
(iii) mobile—maritime/aeronautical/land mobile.

The first of these, DBS, is already well advanced and we are likely to see higher power DBS satellites in the 1985–1990 timeframe, broadcasting directly to the home. Although this is a potential money-spinner there are few new problems for the satellite engineer to solve, although the challenge of producing a cheap and reliable domestic receiver for a mass market is already occupying the ingenuity of engineers. The success or failure of these systems is dependent upon the programme material and not on the satellite technology. The average consumer does not care whether the programmes appear via satellite, cable or any other transmission medium. I will thus not mention this application further in my discussion of future engineering challenges.

The real challenge to the satellite engineer lies in the other two markets with either small fixed business earth-stations or various types of mobile system, for which the broadcast coverage of satellites provides a unique solution. Satellite systems operating to these new markets are already in existence today, for example via the global INMARSAT system to shipping, in the mobile area and the SBS system in the U.S.A. and ECS-SMS and Telecom I business services in Europe. The latter allows the use of 3–5 m antennas which can be situated on the top of a building. However, the satellites currently in use are of the 'dumb' type illustrated in Figure 18. These produce severe limitations for use in these new markets. In the small-station business

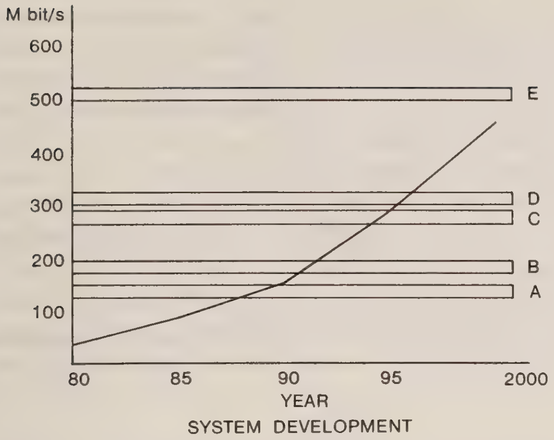



Figure 28. The demand for satellite business services in Europe and the technologies needed to provide them: A. Global coverage; B. Global coverage with regenerative transponders; C. Global coverage with dual polarization; D. Two satellites; E. Multi-beam coverage and regenerative transponders and/or 20/30 GHz

systems they result in either excessively expensive earth-stations (£100ks) for TDMA operation (Telecom I and SBS) or restricted capacity and hence crippling tariffs for FDMA (ECS-SMS). There is a proven demand for such systems, but current dumb satellites cannot satisfy it economically.

This is evidenced in Figure 28, which shows the demand for business services in Europe and their provision by means of various new satellite technologies. It is quite clear that to provide for the demand, the key technologies are:

(i) on-board processing
(ii) multi-beam coverage antennas.

Similar arguments lead to exactly the same conclusion for mobile systems if one incorporates maritime/aeronautical/land mobiles. The satellite needed to provide such services now looks very different to the conventional 'dumb' satellite, and is shown in Figure 29. We have reached the final and fifth era of Table I—the 'intelligent era'.

## INTELLIGENT SATELLITES

Thus our market-driven crossroads also leads us to a technology crossroads, from dumb to intelligent satellites. This involves the placement of computers or processors and sophisticated electronics on board the satellite thus producing an 'on-board-processing' (OBP) satellite. We note from the example shown in Figure 29 that the satellite now has receivers on board which demodulate the information to baseband (e.g. the basic bit-stream) and regenerate it for downward transmission (baseband signal processing). Another important function is the traffic routing or channel-to-beam routing which allows users in different spot beams to communicate. The latter is accomplished by a space switch, and, owing to the buffering needed on reception and prior to transmission we effectively have a time–space–time (T–S–T) arrangement. Such switching arrangements are in fact common in terrestrial telephone exchanges and, at digital baseband rates for instance, are the heart of modern digital exchanges such as the U.K. system-X. What we are therefore effectively attempting is to fly a digital exchange!

Besides the functions of baseband signal processing (regeneration) and traffic or message switching, the presence on board of processing power opens up the possibility of overall systems resource control. This all heralds a new philosophy in satellite systems design, in which the satellite is designed to meet the needs of the user rather than as traditionally the user fitting in with the satellite. Users with a whole range of traffic requirements and capacities

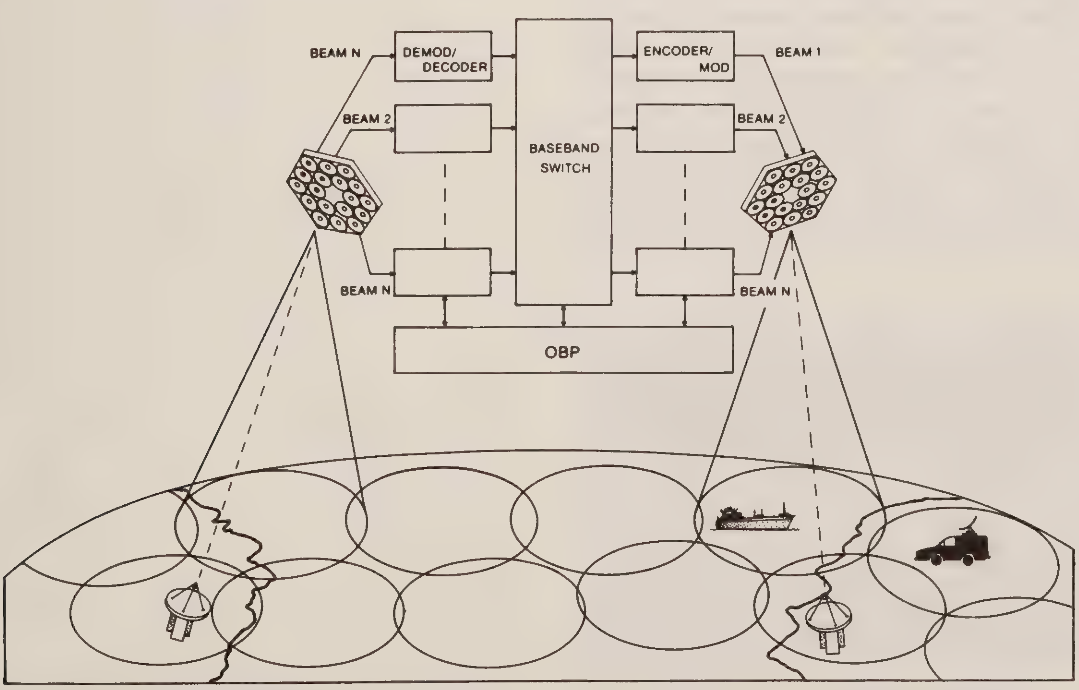



Figure 29. On-board processing ('intelligent') satellite using multiple beam antennas, and on-board switching

can then intercommunicate efficiently via the satellite, which sorts out the relative bit-rates, switches, reformats the information and assembles it into a suitable formats for the transmission and reception by simple and cheap earth-terminals. A particular example of this is shown in Figure 30, which may well be typical of the type of satellite for use with future mixes of mobiles. Here, for simplicity and cheapness of the earth-stations, transmissions are accepted at the satellite on an SCPC basis, but are then transmultiplexed, e.g. converted from a frequency division to a time division format prior to regeneration, baseband switching and reformatting and onward transmission on a simple TDM frame on the down-link. All of this complexity on board the satellite is to make the terrestrial mobile equipment cheap and simple. It could also enable very small (possibly wrist-watch size) receivers to be implemented before the turn of the century.

In 1982/83 a consortium of Universities, including Surrey, conducted a design study for a demonstrator project called CERS (Communication Engineering Research Satellite) to embody many of these new techniques. The aim was to put a small low-cost satellite into a highly elliptical, Molniya type orbit, as shown in Figure 31, which would have the additional advantage of providing a near zenith coverage of northern latitudes for periods of 8–10 hours. Three such satellites appropriately placed in this orbit would provide overhead coverage for mobiles and thus eliminate the shadowing problem associated with mobile coverage from the geostationary orbit at such latitudes. Although multiple beams were not included, all other aspects of OBP previously mentioned could be demonstrated. This included the use of on-board TDMA-control and adaptive resource control in the form of variable transmission rates and forward-error-correction coding which, under processor control (Figure 32) enables each individual earth-station to satellite link to be optimized independently, thus obviating the need for wasteful fixed propagation margins.

The problems that we are facing in the research laboratory today are those of how to build devices such as baseband T–S–T switches, transmultiplexers and on-board TDMA controllers. These subsystems

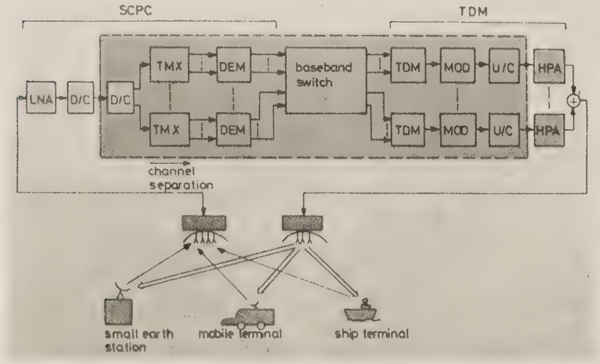



Figure 30. An on-board processing satellite for mobile applications using T–S–T switches and transmultiplexors

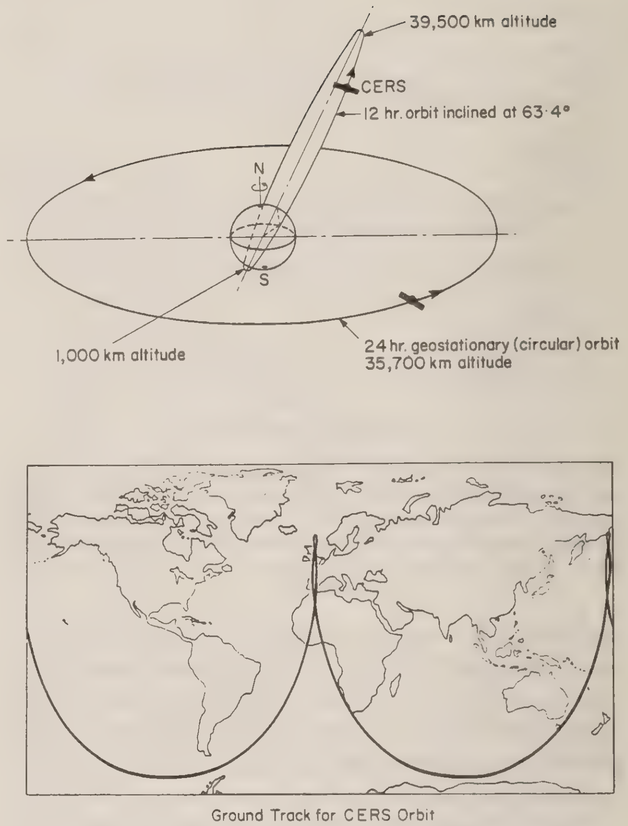



Figure 31. The CERS 'Molniya-type' orbit and earth-track

comprise of processors, memory devices, data buffers and perhaps special processing devices. For any of the applications that we have mentioned, the demands are high in terms of both power dissipation, mass and volume of the on-board equipment. Obviously advances in the range of very large scale integration (VLSI) electronics and in new, high-speed, low-power-dissipation technology, such as

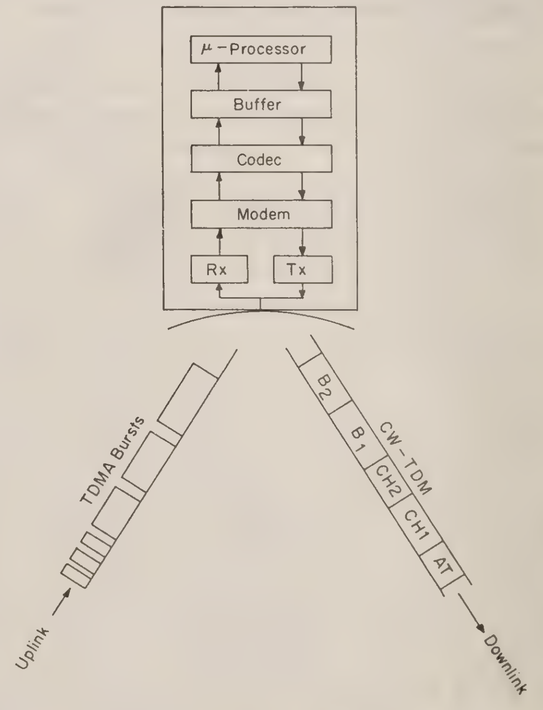



Figure 32. CERS on-board processing concept: operational system configuration

GaAs, will help. An additional problem is that of operation in a high radiation environment. Figure 33 shows the CERS satellite's passage through the radiation belts, which results in high peak dosage. This requires our technology to be radiation hard at the same time as having very low-power dissipation; two characteristics which are usually in opposition, as evidenced in current CMOS technology.

Besides the device technology problems, considerable ingenuity in satellite design is required. Owing to increased satellite lifetime and potential changing roles during the lifetime, a reconfigurable and reprogrammable system is required. This has software implications, as does the overall reliability of our complex satellite. Fault-tolerant software and operating systems are required in order to improve the reliability of the satellites—there is still not much likelihood of a visit from the repair man! A careful balance between the implementation of the fault-tolerance and between hardware and software is in itself a whole new research area.

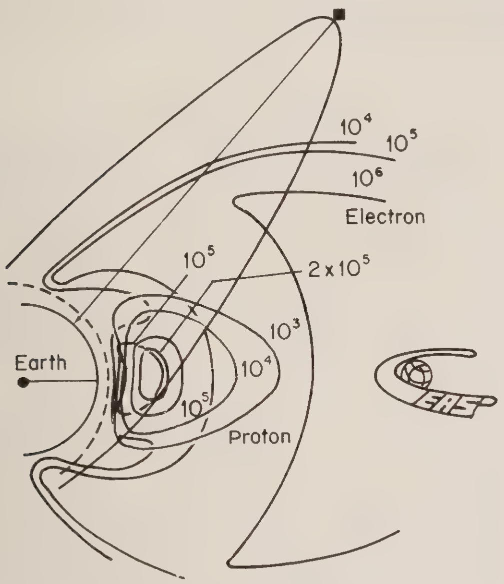



Figure 33. CERS Satellite passage through the earth's radiation belts

## CONCLUSIONS

I have attempted to trace the short, but hectic, history of satellite communications, indicating how technological innovations, many of which emanated from the U.K., have enabled society's needs to be met. I have suggested that we are currently at a crossroads in satellite communications with new markets heralding a new era, with new solutions which lead to the intelligent satellite concept. It is my opinion that Universities and Industry can together exploit this new era to the national benefit. In 1980 when the CERS mission was proposed, the U.K. had a clear lead in on-board processing; a perfect passport to the new markets of the 1990s. I very much regret to say that in 1985 the mission is still no closer to a launch, whereas the U.S.A. and Japan have both announced on-board processing demonstrator missions for the late 1980s.

But not to end on too sombre a note, I can say that our own 'intelligent bird' is indeed taking shape, and in the next year or two should, be flying, at least around our laboratory!

# SATELLITES VERSUS FIBRE OPTIC CABLES*

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SUMMARY

This paper compares the capacities and costs of the new fibre optic submarine cables and the forthcoming INTELSAT VI satellites. The results indicate that, contrary to generally accepted beliefs, satellites are cheaper than fibre optic cables on a per circuit point-to-point basis. Moreover, satellites are shown to possess the advantage of superior overall connectivity capability, in addition to simple point-to-point capacity. This is expected to be very important in the choice of future cost effective facilities.

KEY WORDS Fibre optic cable Costs Satellite

## INTRODUCTION

Recently, there has been much publicity concerning fibre optic telecommunications cable technology. It has been said that the new fibre optic technology for submarine cables would support very large capacity digital transmission systems with a significantly lower per-circuit cost than that realizable with satellite systems. Prior to this evolution in cable technology, the use of satellites for international communications was favoured, in most cases, mainly on economic grounds: although satellites and cables were often viewed as complementary from a diversity point of view. However, the view now being advanced in some quarters, is that fibre optic cables, *per se*, are significantly cheaper than their satellite alternatives. This carries the implication that significant amounts of traffic must shift from satellites to cables over the next decade. Moreover, it has been stated that the propagation delay inherent in satellite links has strengthened the case in favour of fibre optic submarine cables which have significantly shorter path lengths.

The purpose of this paper is to examine these claims and separate myth from reality by comparing satellites and fibre optic cables on a realistic basis, including a cost and capacity comparison of satellites and cables.

## COST AND CAPACITY COMPARISON

In order to examine the validity of the claim that fibre optic cables are cheaper than satellites, an accurate and appropriate comparison methodology must be sought. Unfortunately, the inherent differences between the methods of operation of satellites and cables produce very complex factors that affect the comparison. Most of the results being publicized show fibre optic cables to be less expensive than satellites by comparing the cost per circuit of a single fully loaded fibre optic cable facility with the so-called 'utilization charge' for an INTELSAT voice circuit. To put this in perspective, this means that the capital and operating costs of a single, advanced technology, 100 per cent full, point-to-point fibre optic cable facility is being compared with a globally averaged revenue requirement that embodies a mix of satellite facilities ranging from a relatively low capacity INTELSAT IV spacecraft to plant under construction for the state-of-the-art INTELSAT VI spacecraft, which also reflects far less than full utilization of the satellites in operation. This type of comparison is misleading and is certainly not the correct manner to evaluate the relative economies and efficiencies of the latest cable and satellite technologies.

A more appropriate method of assessing the relative cost efficiencies of the two technologies is to examine the cost per circuit for a fully loaded fibre optic cable facility (e.g. the TAT-8 cable due to be placed in service across the Atlantic in 1988), with the cost per circuit for a comparably equipped fully loaded INTELSAT VI satellite. Details of this comparison are contained in Table I and Figure 1. Two different configurations of the INTELSAT VI spacecraft are used in the comparison. The first is a configuration designed to operate in a multiple access mode and capable of interconnecting several hundreds of different geographical locations. The second configuration is a maximum capacity mode with a single carrier for each transponder and therefore designed to inter-connect relatively few locations—in fact, similar to a typical cable system configuration. Circuit capacity is estimated for both satellite configurations and the TAT-8 cable. These range from the low estimate of the basic bearer circuits on the one hand to a maximum capacity of derived circuits based upon the forthcoming techniques of low rate encoding and circuit multiplication.

Both satellite configurations assume access via three large Standard A earth-stations: one at each of the three TAT-8 landing points (U.S., U.K. and

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Table I. Capacity and cost comparison

| | INTELSAT VI | | TAT-8 |
|---|---|---|---|
| | Operational | Full capacity | |
| *Capacity in circuits* | | | |
| Basic bearer | 22,500 | 26,902 | 7560 |
| FM+TDMA/DSI | 35,000 | | |
| DSI (90 per cent voice, 10 per cent data) | | 63,220 | 17,766 |
| LRE, FM, CFM, TDMA/DSI mix | 55,000 | | |
| LRE(32 kb/s, 90 per cent voice, 10 per cent data) | | 123,750 | 34,776 |
| *Cost estimates* | | | |
| Capital cost (1987) | $232,000,000 | $232,000,000 | $335,400,000 |
| Expected life in years | 10 | 10 | 25 |
| Annual capital costs (14 per cent) | $44,477,541 | $44,477,541 | $48,800,166 |
| Earth-station capital costs (3) | $36,000,000 | $36,000,000 | |
| Expected life in years | 15 | 15 | |
| Annual capital costs (14 per cent) | $5,861,123 | $5,861,123 | |
| Total annualized capital costs | $50,338,664 | $50,338,664 | $48,800,166 |
| Overhead and O & M expenses | | | |
| yearly cable (13·75 per cent of yearly capital) | | | $6,708,000 |
| INTELSAT VI 25 per cent of yearly capital | $11,119,385 | $11,119,385 | |
| E/S 15 per cent of yearly capital costs | $879,168 | $879,168 | |
| Total annualized overhead and O & M | $11,998,554 | $11,998,554 | $6,708,000 |
| Total annualized costs | $62,337,218 | $62,337,218 | $55,508,166 |
| Yearly costs per circuit | | | |
| Capital | $915 | $407 | $1,403 |
| Overhead and O & M | $218 | $97 | $193 |
| Total costs | $1,133 | $504 | $1,596 |
| Ratio IS-VI/TAT-8 | 71·01% | 31·56% | |

France). This ensures a fair comparison by providing a similar communication capability, i.e. by connecting the three cable landing points the satellite is configured to operate in a similar manner to a cable. Each of the three satellite earth-stations is assumed to contain RF, IF, and modem equipment, designed to operate only with large carriers. This has been done to produce a realistic cost structure since the cost of the TAT-8 cable includes only 140 Mb/s digital interface terminal equipment.

The capital costs for both facilities (i.e. the INTELSAT VI satellite and the TAT-8 cable system) are assumed to be incurred in 1987 and are represented as a lump sum, present value, capital cost in Table I. An annualized capital cost estimate is obtained from this figure based upon a 25 year life for the cable and a 10 year life for the satellite using a 14 per cent discount rate. This annualized cost is a constant dollar stream of payments over the life of the facility whose present value (using a

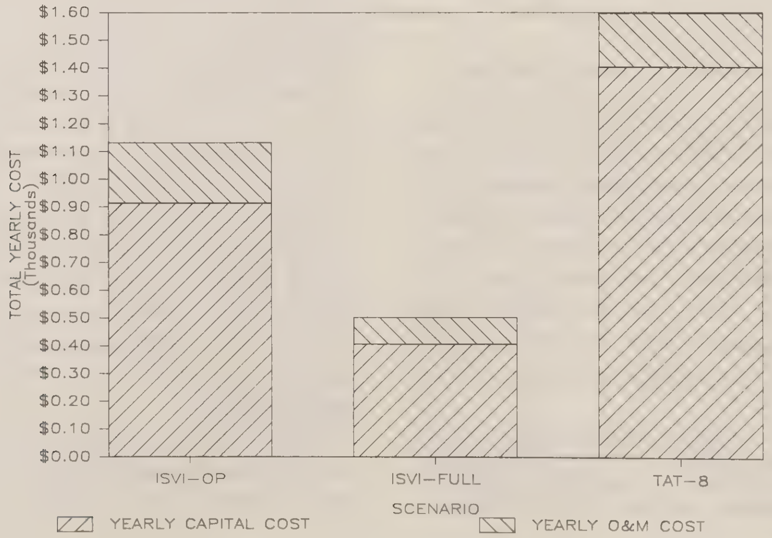


Figure 1. Yearly per circuit costs

discount rate of 14 per cent) equals the lump sum capital cost of the facility.* The capital costs of the three Standard A earth-stations are treated in the same manner by assuming a 15 year life for each facility. Overhead, operations and maintenance expenses for the cable are assumed to be 13·75 per cent of the annualized capital cost incurred each year. Overhead, operations and maintenance expenses for the INTELSAT VI spacecraft are assumed to be 25 per cent of the annualized capital cost incurred each year and 15 per cent of the annualized capital cost for the earth-stations.

The comparative analysis, shown in detail in Table I and Figure 1, yields the following results:

(i) The capacity of the INTELSAT VI is 1·6 to 3·6 times greater than TAT-8 for the operational and maximum capacity configurations, respectively.
(ii) The total annualized cost of the INTELSAT VI (including earth-stations) is only 12 per cent higher than the TAT-8 cable system.
(iii) Assuming 100 per cent fill of both facilities, the annual costs per circuit are given in Table II.†

Table II

| INTELSAT VI | | TAT-8 |
|---|---|---|
| Multi-access configuration | Maximum capacity | |
| $1133/circuit | $504/circuit | $1596/circuit |

These results clearly indicate that, contrary to some generally accepted beliefs, when satellites are compared with the fibre optic cable on an appropriate basis, satellites have lower unit costs.

The TAT-8 cable facility is approximately 6500 km in length. It is estimated that the capital cost of the facility increases by approximately $36,000.00 for each additional kilometre of length. Therefore, the cost per circuit for a trans-Pacific cable from the U.S. to Japan would be approximately $2237 per circuit per year. Since this cost is 40 per cent higher than for TAT-8, the INTELSAT VI has an even bigger cost advantage over fibre optic cables on the longer trans-Pacific routes.

The capacity of the fibre optic cable can be increased by including additional fibre pairs in the cable. It is estimated that each additional fibre pair increases the overall capital cost of the cable by approximately 10 per cent. However, even though capacity can be added to a basic fibre optic system at a relatively low incremental cost, projected circuit demand levels in the late 1980s and 1990s suggest that additional capacity beyond the basic 2-fibre pair system would be far greater than the amount needed to meet demand to most locations.

## CONNECTIVITY

A fibre optic cable is essentially a direct point-to-point facility. However, the technology has developed to permit limited branching from offshore points although branching seems to be cost effective only in connecting very large traffic streams to the main cable system. Moreover, the trend in the development of fibre optic technology is towards greater increases in the maximum capacity for a single facility. This suggests that the technology is far ahead of the needed demand for circuit capacity between terminal points. Therefore, in order to use fibre optic submarine cable facilities efficiently, extensive terrestrial or satellite networks are needed in conjunction with the cables to carry traffic beyond the terminal points of the cable. In contrast, the distinct advantage of satellite technology is the extensive connectivity available through a single facility. One satellite is capable of directly serving an extremely large number of points located within the beam coverage of the satellite. For example, the connectivity in INTELSAT's Atlantic Ocean region currently accommodates 448 independent traffic paths covering North America, South America, Europe, Africa and the Middle East. New paths are created simply by adding additional earth-stations to access the satellite. Furthermore, satellite technology is such that the cost of providing service is essentially distance insensitive within the beam coverage of the satellite. This means that it costs no more to deliver the signal directly to the user than it does to down-link through a coastal earth-station, which then requires the use of additional terrestrial facilities to deliver the signal ultimately to the user. A key point to stress is that state-of-the-art satellites and cables both have capacities far in excess of projected point-to-point requirements to most locations; therefore, the cost effective use of transmission facilities will depend critically on connectivity capability. This suggests that 'economies of scope' as well as 'economies of scale' should be considered in evaluating satellites and cables.

* This annualized cost is equivalent, in present value terms, to a stream consisting of straight-line depreciation payments and a return on net book value of 14 per cent. Also, the annualized cost adjusts for the different estimated lives of the two facilities, since it is equivalent to continuous replacement of each facility at end-of-life, assuming a constant replacement cost. (A sensitivity analysis was conducted using a higher discount rate of 17 per cent. This shifted the results even more favourably towards the satellite.)

† The relative difference in cost per circuit between satellite and cable will not change if less than 100 per cent fill is assumed, as long as the percentage use is the same for both facilities. For example, if 25 per cent fill is assumed, the per circuit costs are $4534 and $2016 for the two satellite configurations and $6384 for TAT-8.

## PROPAGATION DELAY

Recurring claims have been made that satellite transmission facilities are inferior to cable systems because of the propagation delay inherent in transmitting 22,500 miles up to the satellite and then back to the earth's surface. Developments in echo suppression technology have virtually eliminated the subjectively distressing delayed echo associated with voice transmissions carried on satellites. In addition, delay compensation units have been developed for data transmissions via satellite. This has resulted in extremely satisfactory satellite data services.

## CONCLUSIONS

The analysis has demonstrated that when satellites and fibre optic cables are evaluated on a comparable basis, satellites are more cost effective than their cable counterparts. Moreover, connectivity capability, not point-to-point pipeline capacity, is the key to cost effective use of communications transmission facilities in the 1980s and 1990s, since the overall capacity available in both satellites and cables exceeds the foreseeable demand. Satellites have a significant advantage over cables in that they can provide connectivity whose costs are insensitive to distance, broad geographical coverage, and extensive multiple access capability.

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# KU-BAND SATELLITE DIGITAL TRANSMISSION SYSTEMS

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## SUMMARY

A nation-wide data communications service is being placed in service by a major telecommunications carrier. This service will rely on a satellite network being provided and installed by Harris Satellite Communications Corporation.

The network supports information data rates from 56 kb/s to 2·048 Mb/s. This data communications network has been architectured to include a number of innovative monitor and control functions, up-link power control, modular equipment shelter design and a modular antenna/feed subsystem.

This paper will detail this application.

KEY WORDS Ku-band Digital network

## INTRODUCTION

The digital network is implemented by the installation of a number of small-aperture (3·5 m) earth-stations on the customer's premises.

Digital transmission rates from 56 kb/s to 2·048 Mb/s can be supported. The information data rate used is adjusted to suit the subscriber's service requirements.

Transmission through the satellite is provided by QPSK/BPSK modulated individual SCPC carriers. These carriers are scheduled and managed through the network's automatic monitor and control master station in Atlanta, Georgia. This network is designed to operate in any 'Ku-band' transponder across the geosynchronous orbital arc from 69° to 139°W longitude from any location in the contiguous 48 states of the U.S.A.

Multiple transponder access is available by the system's use of a frequency-agile RF terminal (RFT) and a frequency-agile QPSK/BPSK modem.

The system's design availability objective is 99·6 per cent. The remaining 0·4 per cent is split equally between equipment outages and rain attenuation.

## SYSTEM TECHNICAL DESCRIPTION

A simplified functional block diagram for the single-thread remote-site earth-station subsystem is shown in Figure 1, excluding the customer's unique baseband digital interface, which is a subscriber service dependent element.

The transmit and receive subsystem elements, followed by the master and remote sites and the monitor/control subsystem will be detailed in the following sections.

## TRANSMIT SUBSYSTEM

Immediately following the baseband interface, the up-link signal is processed through a forward error correcting codec. This codec is designed to allow the coding rate to be selected from among 3/4, 7/8 or 1/2, as required, to optimize the use of the available satellite's bandwidth and down-link e.i.r.p.

Modulation of the digital bit stream at the required data rate, as seen at the FEC output, is provided by a QPSK/BPSK modem. This frequency-agile modem provides an RF carrier at its output in the 52–88 MHz frequency band at a frequency stability of $10^{-6}$.

A frequency-agile up-converter translates the input IF band to the 14·0 to 14·5 GHz frequency band. This converter allows the remote selection of any one of 99 predetermined frequencies to be selected. These frequency selections are prestored in programmable read-only memories (PROMs) within the up-converters.

Power amplification is obtained with a 70 W travelling wave tube amplifier. The required value of up-link e.i.r.p. is adjusted with variable attenuators in the interfacility link (IFL). The required harmonic reject filter and the receive band noise power reject filter are contained within the HPA.

## RECEIVE SUBSYSTEM

The receive subsystem's $G/T$ is established with a 190 K low-noise amplifier converter module. This unit not only provides the required 'Ku-band' low noise amplification, but also down-converts the entire 'Ku-band' to 'C-band'.

A 'C-band' down-converter following the low noise conversion (LNC), allows the selection of any of the 'Ku-band' transponders. Any one of 99 previously programmed frequencies may be either locally or remotely selected. The down-converter's IF output in the 52 to 88 MHz band is then passed through the IFL to the modem.

Final down-conversion of the IF band is provided by the demodulator segment of the modem. This

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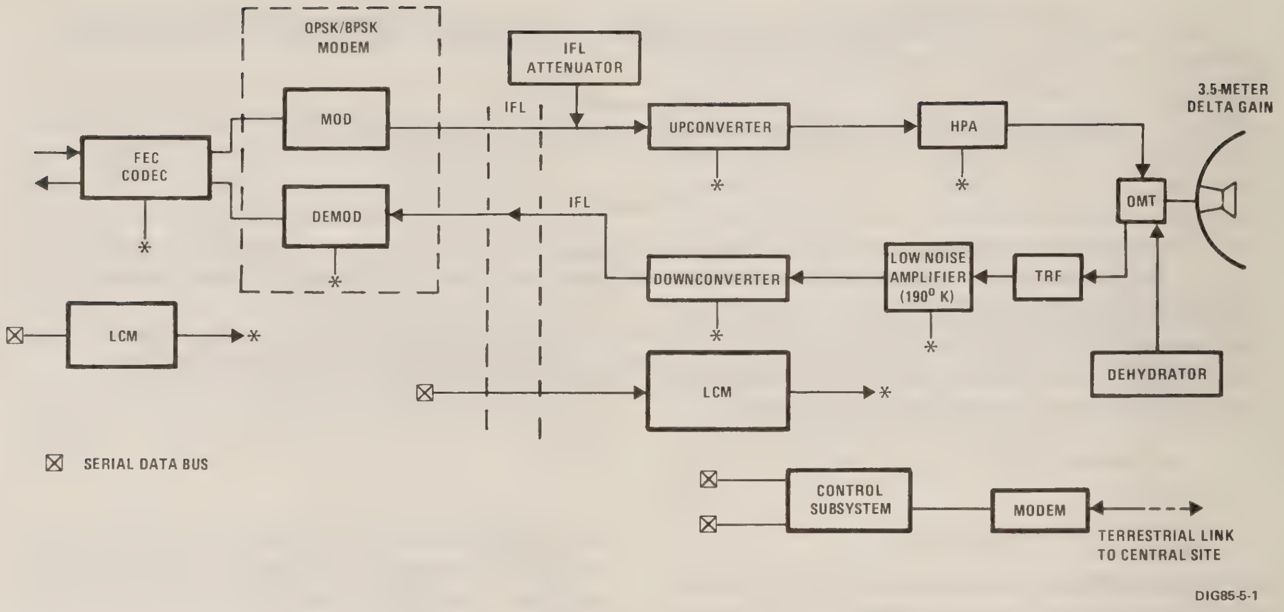


Figure 1. SCPC earth-station functional block diagram

modem is frequency-agile and can be assigned to demodulate any one of the SCPC carriers within the intermediate frequency bandwidth.

The final step in the down-link receive path is the processing of the digital bit stream through the FEC codec. The codec is selectable in its rate as detailed in the up-link path description.

## MASTER SITE

The master site for this data communications network is located in Atlanta, Georgia.

It is a roof-top mounted, fully redundant ground station as shown in Figures 2 and 3. The two subsystem elements (i.e. antenna assembly and equipment enclosure) are both mounted to a load frame assembly.

The load frame assembly provides the mounting points required for the antenna assembly and the equipment shelter. It transfers the load's forces and moments to the skeletal structure of the building by being mounted on extensions of three of the building's columns. These column extensions can readily be seen in Figures 2 and 3.

A functional block diagram of this master site is shown in Figure 4. As can be seen from this functional block diagram, the equipment shelter contains a redundant configuration of the same hardware elements used in the low-profile remote ground stations.

Figure 2. Master site

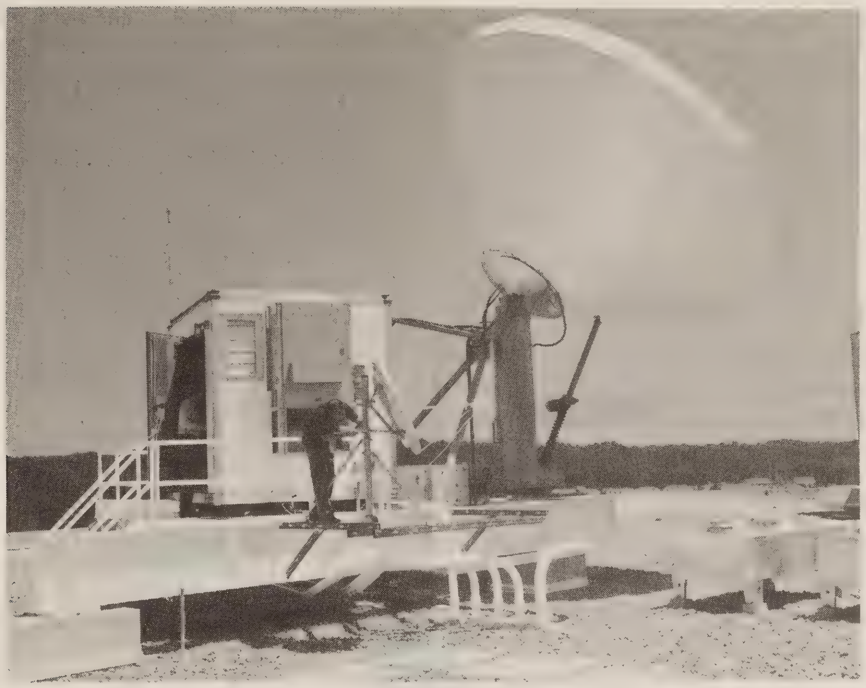

Figure 3. Master site

*Antenna subsystem*

The Harris 6·1-meter Delta Gain® Ku-band antenna, is an expansion of the revolutionary Delta Gain antenna line. The antenna provides exceptional performance for receive-only and transmit–receive applications.

The antenna features an all-aluminium reflector which incorporates precision-formed panels, radials and hub assembly with matched tooling for ease of assembly without field alignment. The unique back-up structure completely encloses the rear of the antenna, providing strength and environmental protection.

The reflector coupled with an azimuth/elevation steel kingpost pedestal provides the stiffness and pointing accuracy required for Ku-band operation. The system is designed for full U.S. domestic orbital arc coverage. In the motorized version, simultaneous azimuth, elevation and polarization drive

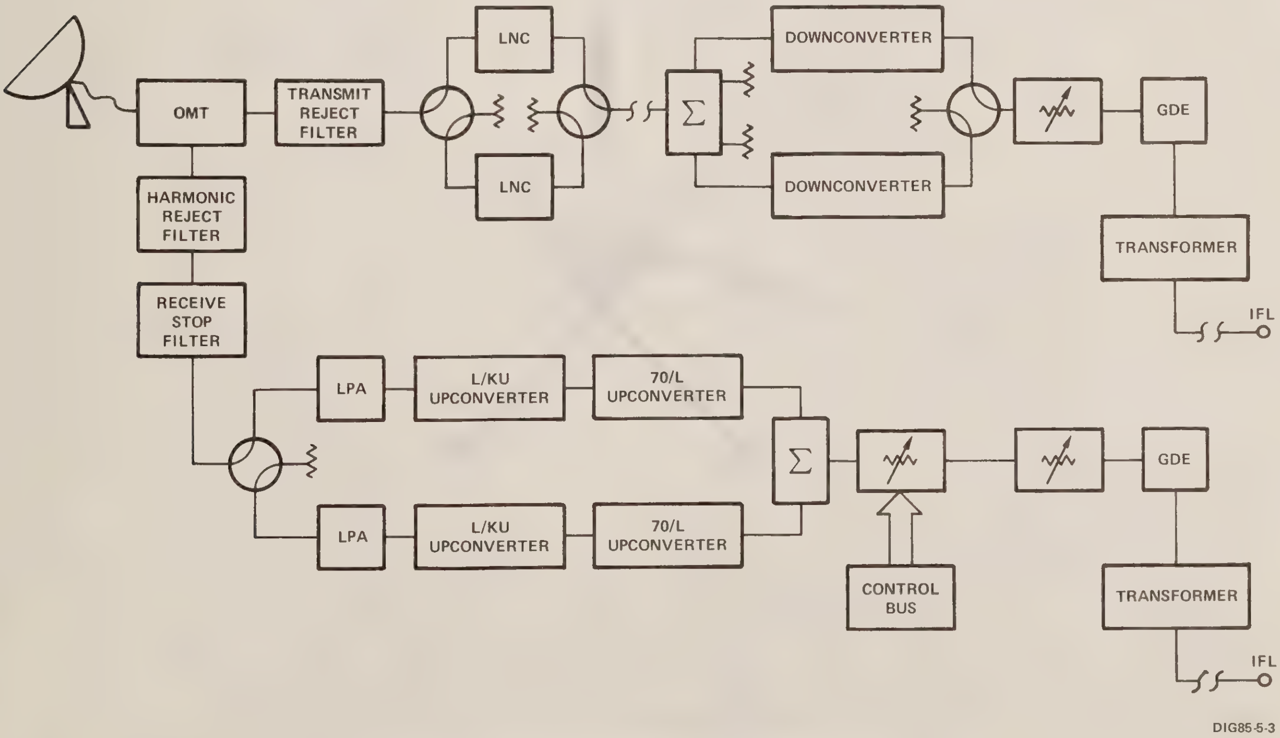


Figure 4. Master site, in Atlanta, block diagram

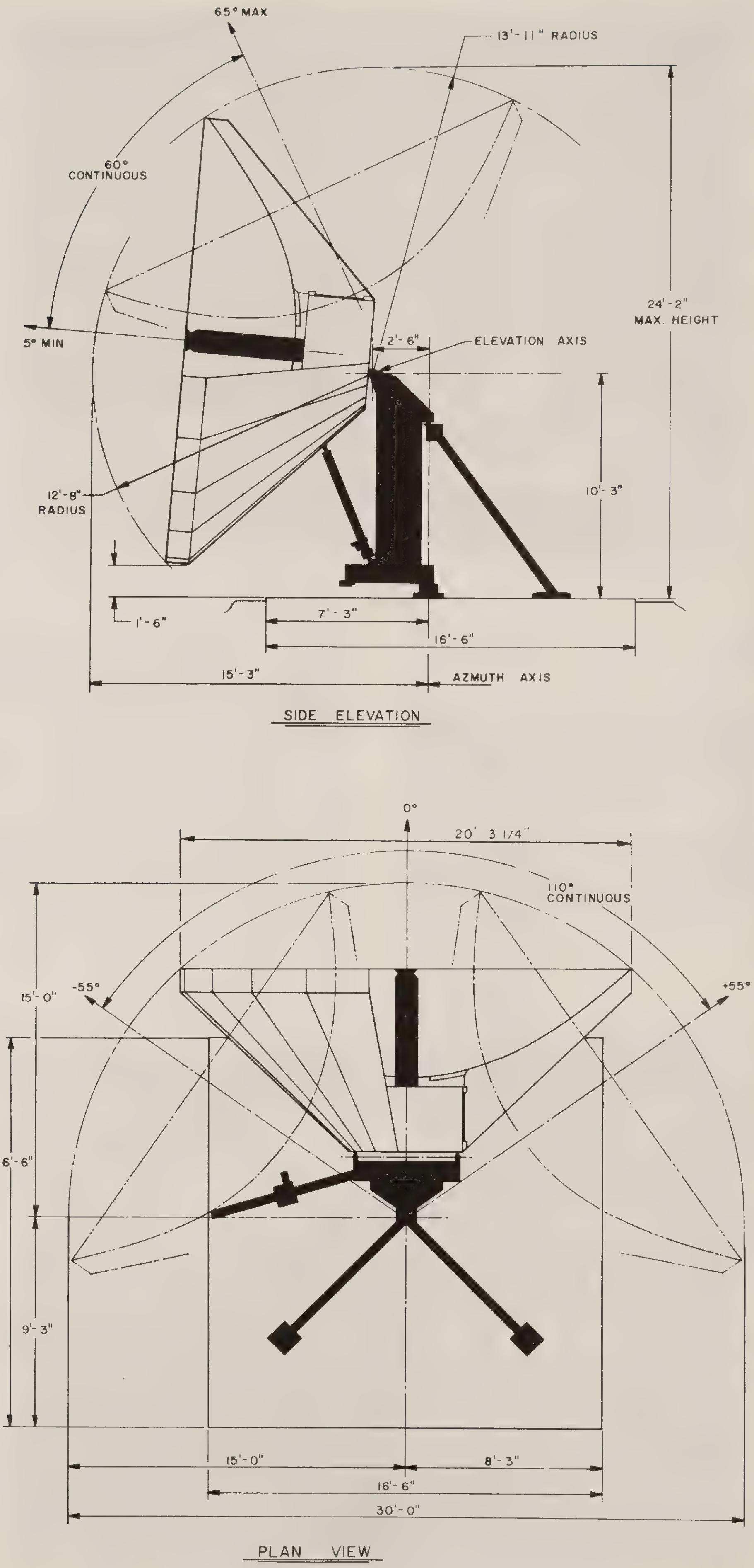


Figure 5. 6·1 m Delta Gain Ku-band earth-station antenna

Table I. Mechanical features

| | |
|---|---|
| Diameter: | 6·1 m |
| Azimuth travel: | 110° continuous |
| Azimuth travel rate: | 1·8°/s |
| Elevation travel: | 5° to 65° continuous |
| Elevation travel rate: | 1·0°/s |
| Polarization travel: | ±90° |
| Polarization travel rate: | 1·5°/s |
| Weight—reflector: | 1600 lb (726 kg) |
| Weight—pedestal: | 1700 lb (771 kg) |
| Shipping weight (typical): | 4350 lb (1973 kg) |
| Shipping volume: | 1500 $ft^3$ (42·5 $m^3$) |
| Finishes: | Reflector panels: reflector surface heat-diffusing white paint<br>Pedestal: red oxide primer, two top coats of enamel |
| Surface accuracy: | 0·020 inch static (0·51 mm) |
| Foundation size: | 16·5 ft × 16·5 ft × 1·5 ft (5·0 m × 5·0 m × 0·46 m) |
| Concrete volume: | 15·5 $yd^3$ (11·8 $m^3$) |
| Reinforcing steel: | 1460 lb (662 kg) |
| Soil bearing pressure: | 2000 lb/$ft^3$ (10,000 kg/$m^3$) |

allows switch-over between any two U.S. domestic satellites in 60 s or less at most U.S. locations.

The side elevation and the plan view of this antenna are shown in Figure 5. The mechanical features, the environmental specifications and the typical electrical specifications are listed in Tables I–III.

*Redundant equipment enclosure*

The earth-station equipment shelter houses the complete RF equipment subsystem from the inter-facility link (IFL) at 70 MHz to the antenna feed subsystem at 'Ku-band'.

The building is an all-aluminium enclosure that provides the required value of thermal quality by using a rigid insulation dual-wall construction.

A view of the interior showing the equipment rack elevations is shown in Figure 6. The shelter has been sized to allow the service personnel easy

Table II. Environmental specifications

| | |
|---|---|
| Operational winds: | 45 m.p.h. (72 km/h); gusts to 60 m.p.h. (97 km/h) |
| Survival winds (any position): | 125 m.p.h. (200 km/h) |
| Ambient temperature (survival): | −25° to 70°C (−13° to 158°F) |
| Rain (operational and survival): | Up to 4 inch/h (10 cm/h) |
| Relative humidity (operational and survival): | 0 to 100 per cent with condensation |
| Solar radiation: | 360 BTU/h/$ft^2$ (1000 kcal/h/$m^2$) |
| Radial ice (operational): | 0·25 inch (0·6 cm) on all surfaces except reflector, with de-icing heaters energized |
| Radial ice (survival): | 1 inch (2·5 cm) on all surfaces; 0·5 inch (1·3 cm) on all surfaces with 80 m.p.h. (130 km/h) wind gusts |
| Shock and vibration: | As encountered during shipment by commercial air, rail or truck |
| Corrosive atmosphere: | As encountered in coastal regions and/or heavily industrialized areas |
| Seismic (survival): | 0·3 g horizontal; 0·1 g vertical |

Table III. Electrical specifications

| | 6·1 m | |
|---|---|---|
| | Receive | Transmit |
| Frequency: | 11·95 GHz | 14·25 GHz |
| Gain at 12–14 GHz (2-port feed): | 55·4 dBi | 56·5 dBi |
| VSWR | 1·3 : 1 | 1·3 : 1 |
| Beamwidth, −3 dB | 0·28° | 0·24° |
| Antenna noise temperature, K | | |
| 5° elevation | 74 | |
| 10° elevation | 60 | |
| 20° elevation | 50 | |
| 40° elevation | 44 | |
| Power handling capability: | | 1 kW |
| Feed interface: | CPR 75G | CPR 75G |
| Port-to-port isolation: | | |
| Transmit-to-receive | | 30 dB |
| Receive-to-receive, linear | 35 dB | |
| Cross-polarization | 35 dB | 35 dB |
| Discrimination on axis: | | |
| Within 1 dB contour | 30 dB | 30 dB |

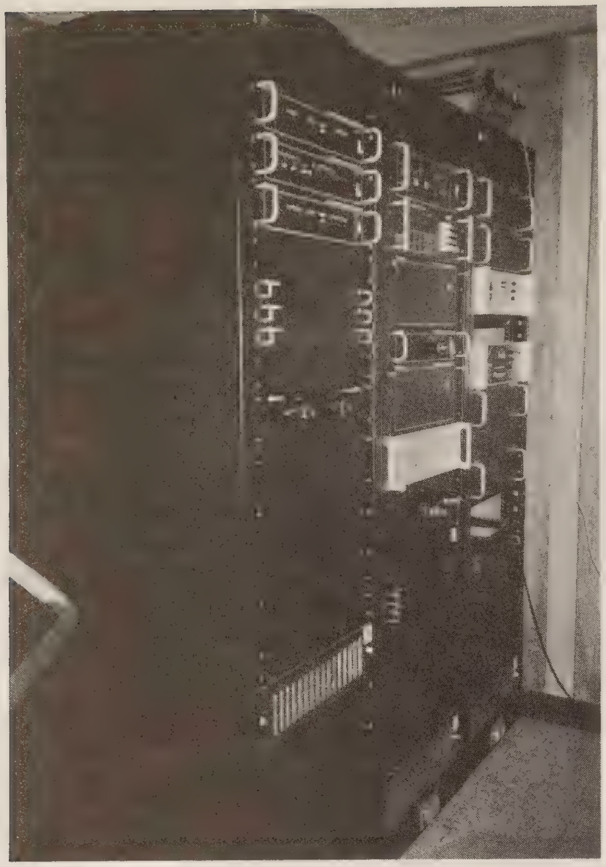

Figure 6. Redundant equipment shelter interior view (Atlanta)

access to all the hardware elements and some expansion space for future equipment additions.

## REMOTE SITE

The remote sites are equipped with a 3·5 m kingpost-mounted antenna and a low profile equipment shelter assembly, designed specifically for roof-top mounting.

A typical roof-top-mounted ground station is shown in Figure 7, as seen from the street elevation and from the roof itself in Figures 8 and 9, respectively.

As can be readily seen in these Figures, there is a considerable functional similarity to the master site roof-mount in Atlanta.

Figure 7. Kansas City remote site

Figure 8. Remote site roof-mount

A load frame that integrates the low-profile shelter and antenna assembly subsystem is used to translate the load forces and moments to the skeletal structure of the building.

### *3·5 m antenna subsystem*

The Harris Delta Gain 3·5 m 'Ku-band' antenna subsystem has been designed and provided to be fully compliant to the FCC 2° spacing rule.

A kingpost antenna mounting assembly is used with a precision pointing capability in azimuth and elevation. There is a similarity of this assembly to the 6·1 m design used on the master site.

In the case of the 3·5 m kingpost, no backside support elements are required to the top of the kingpost.

The main reflector assembly is provided as a precision hub structure and four petal assemblies that are field assembled.

Each of these main reflector quarter sections is composed of three panels that have been factory aligned and permanently assembled. This design allows the entire antenna subsystem to be placed in an elevator and easily placed on the building roof.

A simple assembly of the entire antenna and feed subsystem on the roof is all that is required. The design has been provided such that it cannot be assembled either incorrectly or with a misalignment in the field.

A complete main reflector and a feed subreflector de-icing kit is available for sites where this is required. In addition, a fully motorized drive assembly for azimuth and elevation is available for service that requires a satellite-to-satellite agility.

### *Low-profile equipment shelter*

A fully modular equipment shelter assembly is provided. This unit is composed of two basic types of module assemblies, as shown in Figure 10.

The power distribution, circuit breakers and dehydrator equipment are provided in a single module. Each earth-station requires one of these modules.

A second type of module is used, which is the

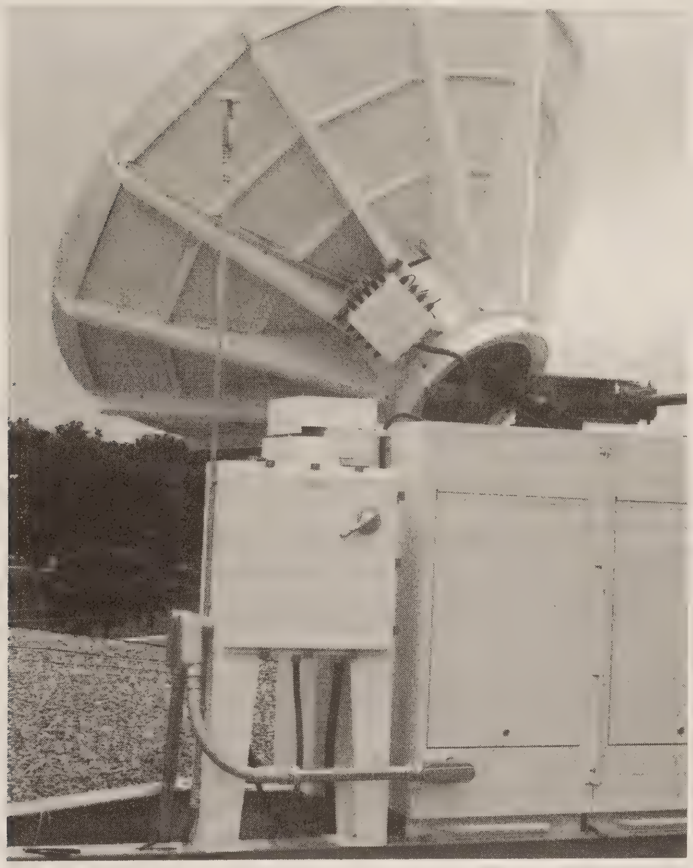

Figure 9. Remote site roof-mount

equipment module. These are placed adjacent to the first module and repeated as many times as required to accommodate the earth-station equipment.

A typical single-thread earth-station can be integrated into a total of three modules, as shown in Figure 10. Cooling of the earth-station is provided by an air-conditioning assembly that is mounted directly on the power distribution module.

An air exchange handler is provided on the side of the last equipment module. This handler prevents the earth-station from overheating should the air-conditioning subassembly fail. These air flow paths are detailed in Figure 11.

Two air plenums are integrated within these equipment modules (see Figure 11) and provide a fully closed loop cooling path.

In the event of an air-conditioner failure, the air handler power exhaust fans will turn on and the external vents are powered open to exhaust the heated air from the upper plenum and to allow external air into lower plenum unit.

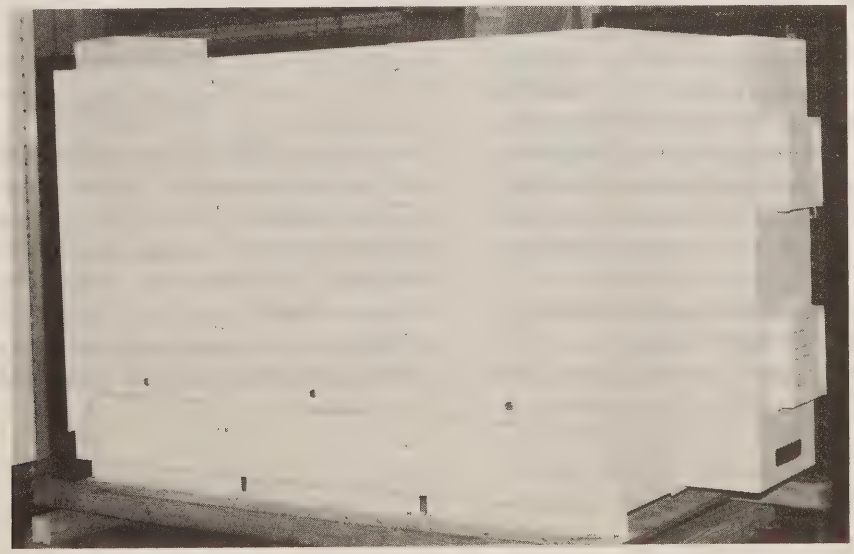

Figure 10. Remote site low profile shelter assembly

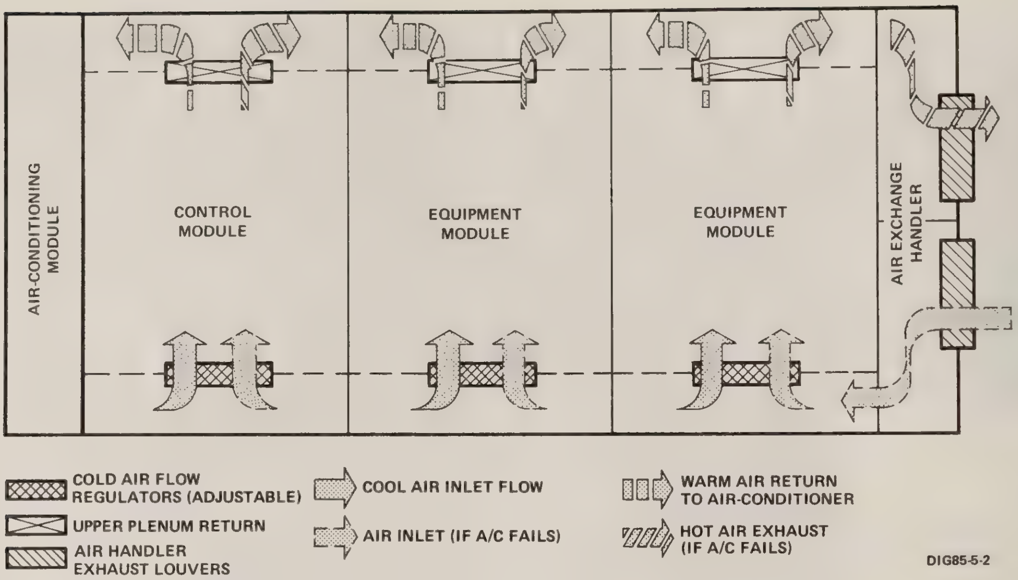


Figure 11. Low profile shelter assembly thermal characteristics

## MONITOR AND CONTROL SUBSYSTEM

The monitor and control function for the network is architectured as a distributed microprocessor based system.

Each ground station is locally monitored and controlled by a microprocessor at the ground station.

A pair of local control and monitor (LCM) interface modules are provided at the earth-station. One is used to interface the equipment at the baseband side of the interfacility link (IFL) and the second is co-located with the RF terminal (RFT) shelter on the roof of the customer site.

Instructions from the local microprocessor CPU are formatted on a serial bit stream bus (i.e. RS-449) and forwarded to the LCM. The LCM module provides the required interface formatting, isolation and level changes to execute either a status change or to monitor a parameter.

Each LCM has a unique programmable address and can either be instructed by the local microprocessor or remotely through the terrestrial link.

The control and status monitoring of all the earth-station's functions, as an element of the communication network, is administered by the master site at Atlanta, Georgia through the terrestrial link.

Some of the typical control and monitor functions executed via the monitor and control subsystem are:

(a) transponder spectrum and power analysis
(b) end-to-end bit error rate testing
(c) trouble isolation and routine preventive maintenance
(d) link establishment and take down
(e) earth-station status tracking
(f) integration and testing of new equipment
(g) earth-station commissioning
(h) earth-station transmit on/off.

## OPERATION AND MAINTENANCE

Although the system is designed for unattended operation, it does require periodic maintenance. In the event of a failure in the earth-station, the local control and monitor (LCM) unit reports this failure locally in the baseband equipment room and remotely to the Network Control Center (NCC) at Atlanta, Georgia.

The NCC will then notify the Maintenance Group of the failure and the location of the replacement spare. This spare might be resident at a depot or on a field repair vehicle in the neighbouring area.

## CONCLUSIONS

During the 1980s, corporations and common carrier service companies will see an explosive growth in the volume and variety of Ku-band satellite communications services, as new and innovative hardware and software subsystem elements are made available.

The era of customized satellite communication services for businesses, at viably competitive rates, has arrived.

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# MEASUREMENTS OF THE TIME STATISTICS OF FMTV SPECTRA AND TV INTERFERENCE INTO FDM/FM CARRIERS

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## SUMMARY

When computing the amount of interference from FMTV signals in satellite systems, it is customary to consider that the only effective TV modulation is the energy dispersal signal (EDS). This leads to a sufficient but highly conservative system design, since for most of the time the wanted demodulated signal may experience interference levels well below that computed using this approach. If the time statistics of the interference can be determined through measurement, then a grade-of-service approach can be taken in which interference can be guaranteed not to exceed a certain level for more than a prescribed fraction of the time. This approach will lead to more efficient use of orbit/spectrum resources as a result of the implementation of less conservative system designs.

This paper presents a simulation approach used to 'measure' FMTV power spectra with and without EDS and the corresponding interference powers into the basebands of FDM/FM carriers. Time statistics in the form of FMTV spectral masks and FDM baseband interference power time distributions have been derived from the measured data of 1000 off-air TV frames for co-channel TV and standard FDM/FM carrier sets (12 to 1200 channels) deployed by INTELSAT. Sample results are given.

KEY WORDS TV time statistics Interference FDM/FM

## 1. INTRODUCTION

This paper presents a simulation approach which is used to 'measure' the FM power spectra of TV signals and the corresponding interference power into the basebands of FDM/FM carriers. The need for this measurement system arises from the requirement for an accurate method of FDM baseband interference assessment.

One thousand off-air TV frames were digitized using a frame grabber. The digitized samples (8 bits/sample) of these TV frames were then processed by a computer program which simulates an ideal FM modulator. The output of the program is the FM spectrum of the input TV frame with and without EDS being added. The power spectra of the wanted INTELSAT FDM/FM carriers were generated by a white noise loading simulation. The interference power into the baseband of an FDM/FM carrier was computed by convolving the interfering FMTV and the wanted FDM/FM RF spectra. Spectral masks were then derived from the 'measured' FMTV spectra based on peak power densities, and the worst-channel interference power time distributions were computed for the FDM/FM carriers.

## 2. SYSTEM OVERVIEW

Figure 1 depicts the functional block diagram of the measurement system used to generate the time statistics of the FMTV power spectra and TV interference into FDM/FM carriers. All processing shown in the Figure, except for the collection of off-air colour TV signal samples, is implemented in software. The system can be divided into five subsystems, each handling a specific task, namely (1) collection of colour video signal samples, (2) generation of FMTV power spectra, (3) generation of FDM/FM power spectra, (4) calculation of FDM baseband interference and (5) calculation of FMTV spectral masks and FDM baseband interference power distribution.

Descriptions of each of the subsystems are given in the following sections. Detailed examination of the generation of FMTV spectra is given in Section 4. It should be noted that only NTSC video format was addressed in this study. However, PAL and SECAM formats can be examined with only slight modification to the software. Nevertheless, a new database of off-air collected TV frames may be

* The work reported in this paper was performed while this author was with Miller Communications Systems Ltd.

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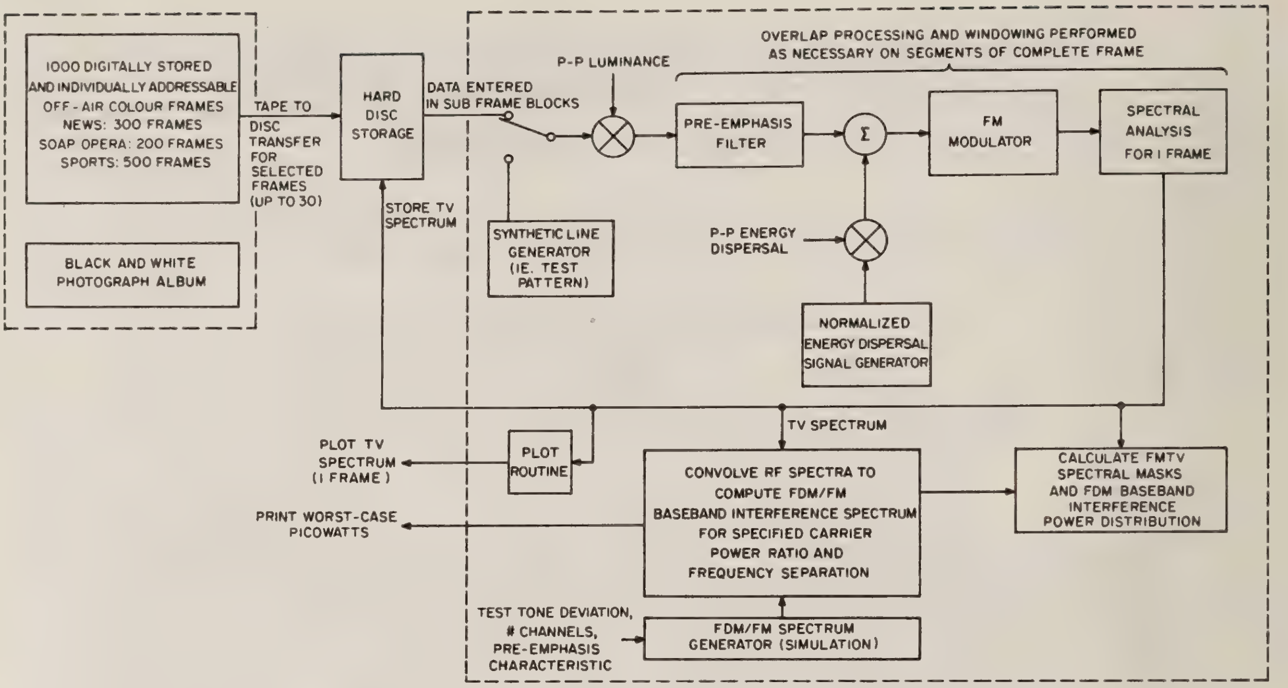


Figure 1. Basic TV spectral and picowatt interference analysis software

required, as transformation from NTSC to these standards does not appear to be feasible.

## 3. COLLECTION OF OFF-AIR VIDEO SIGNAL SAMPLES

The video signal samples of 1000 off-air TV frames were collected. These 1000 frames represent various broadcast television programmes, namely news programmes, soap opera programmes and sports programmes. Figure 2 shows the network configuration for the collection of digitized samples of the frames. The operation of the network is described below.

The broadcast television signal is demodulated by a commercial TV receiver whose video output is filtered by a 7th order elliptic lowpass filter with cut-off frequency of 4·25 MHz. The frame grabber can capture an entire video frame on command by sampling the video signal at a 9·3329 MHz rate and digitizing it using a linear 8-bit A/D converter. The digitized video signal samples are stored in the memory of the frame grabber and then transferred to magnetic tape mass storage through a PDP-11/44 minicomputer.

The video signal samples of the 1000 digitized frames stored on magnetic tapes are accessable on a frame-by-frame basis. Only the non-systematic part of each horizontal line of the frame is sampled and stored. The equalizing pulses, vertical sync pulse, horizontal sync pulse and the colour burst are excluded. The samples of these pulses are generated (synthetically) and added to the measured samples to form the complete TV signal. Note that the audio subcarrier is not included in the measured signal samples.

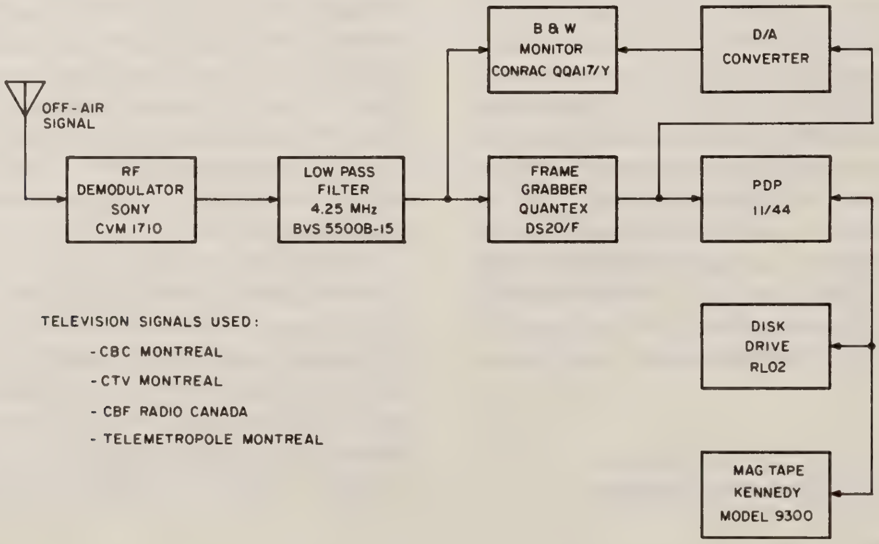


Figure 2. Block diagram of frame digitization equipment

## 4. GENERATION OF FMTV POWER SPECTRA

With a sampling rate of 9·3329 MHz, a TV frame consists of about 310,000 signal samples. In addition, since the RF bandwidth of the FMTV signal is of the order of 38 MHz (15 MHz peak-to-peak picture deviation was assumed), some 1,240,000 samples are required to represent a single modulated frame. These figures are impractical, if not impossible, for most computers since the amount of memory required to store the signal samples would be enormous. An alternative method which estimates the RF spectrum of a TV frame by averaging the spectra of overlapping time segments of the complete frame is discussed below. This approach was found to produce accurate results by comparison of the FM power spectrum of one horizontal line of a colour bar frame and that of the whole frame. In addition, this approach is very effective for simulation of EDS which will be discussed later.

### *System design*

The TV frame (33·3 ms long) is divided into small time segments whose FM spectra are computed and averaged to produce a 'smoothed' FM spectrum of a TV frame. To avoid the 'end effects' due to circular convolution introduced by the pre-emphasis and integration filtering operations, the overlap and save method[1] is employed. In addition, an overlapping and windowing technique[2] is used on the RF time segments (i.e. the signal segments at the FM modulator output) to improve the frequency selectivity and the accuracy of the 'smoothed' spectrum.

A number of system parameters that influence the design of the simulation program had to be determined. The first parameter is the length of the segment. The natural choice would be a single horizontal line (63.55 $\mu$s long). With a sampling rate of 9·3329 MHz, the number of signal samples per line is 593, which cannot be handled efficiently by an FFT routine (not a power of 2). Furthermore, use of a line would result in greater, and in exceptional circumstances systematic, error because luminance transitions from one line to another would consistently not be represented in the spectra of the individual (non-overlapping) segments from which the frame spectrum is estimated. As a result, we used a segment length of 54·87 $\mu$s (i.e. 512 samples per segment). This choice yields a baseband frequency resolution of 18·23 kHz.

A sampling rate of 9·3329 MHz is sufficient for the baseband video signal since it is greater than the Nyquist rate of the video signal (8·4 MHz). However, this sampling rate is too small to represent the FM modulated signal since the FMTV Carson's rule bandwidth is about 38 MHz, assuming a 15 MHz peak-to-peak picture deviation. Thus, the sampling rate had to be increased to accommodate the required RF signal bandwidth. A sampling rate of 37·33 MHz (i.e. an increase of 4 times from 9·3329 MHz) was used. This rate, which is large enough to avoid aliasing error, results in an array size (2048 points with an 18·23 kHz frequency resolution) acceptable for FFT processing.

The next step was to design a system that can produce the 37·33 MHz wide spectrum of a segment 54·87 $\mu$s long. Apart from the addition of EDS to the video signal, Figure 3(a) shows the simulation block diagram of such a system. Figures 3(b) and 3(c) show the detailed block diagrams indicating how the $\sin(x)/x$ interpolation (adding zeros in the frequency domain) and the integration algorithms are implemented, respectively. A modified integration algorithm is needed, since numeri-

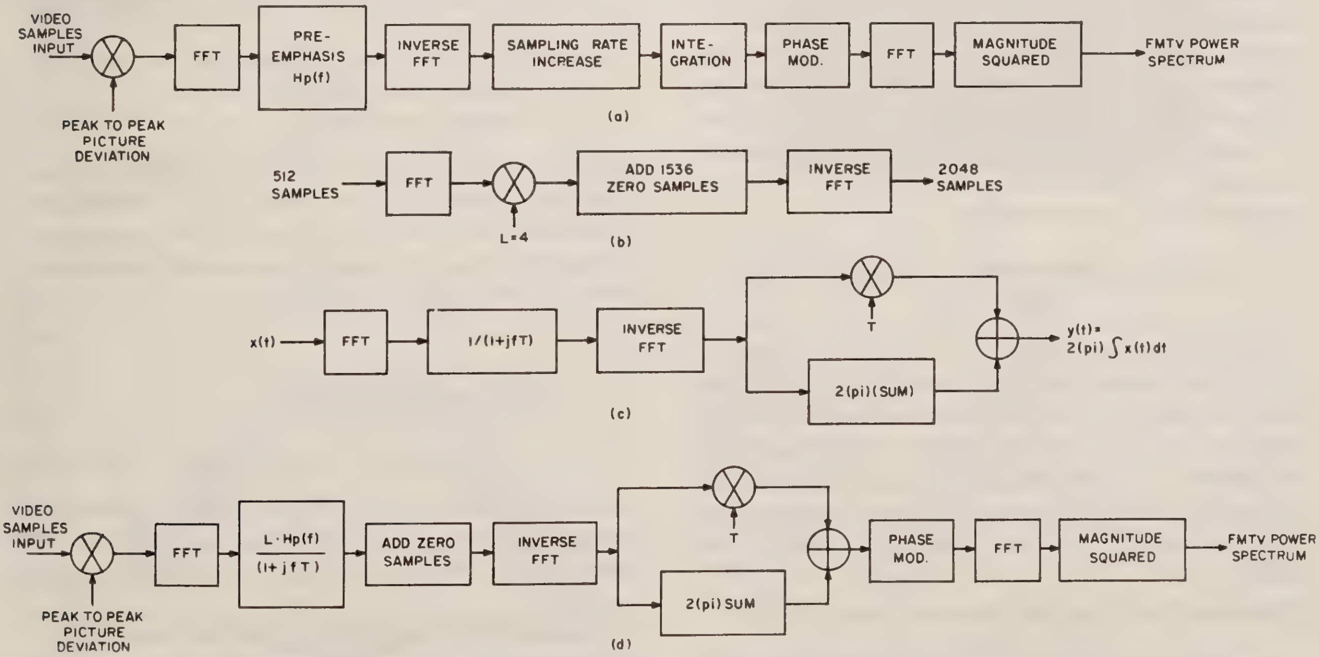


Figure 3. (a) Simulation block diagram of the FMTV spectrum generator; (b) block diagram shows how the sampling rate is increased; (c) implementation of the integrator; (d) implementation of the FMTV spectrum generator

cal calculation of the integral of the video signal cannot be done by simply dividing the frequency domain samples by $2\pi f$ because the result is undefined for $f=0$ (i.e. for a DC component), nor can it be done by simply summing the time domain samples because this method does not give the required accuracy at higher frequencies. The approach taken was to integrate highpass signal components in the frequency domain and lowpass components in the time domain. Figure 3(d) shows how the complete simulation model is implemented in software.

*Simulation of energy dispersal signal*

The EDS specified by INTELSAT for the NTSC system is a 30 Hz symmetrical triangular waveform with its apexes fixed at the vertical blanking interval.[3] The EDS can be simulated by directly adding it to the baseband video signal after pre-emphasis, as shown in Figure 1. This approach, however, has the disadvantage of increasing the computation time required to generate the FMTV spectra if more than one EDS is to be simulated. Therefore, an alternative approach is employed. This approach assumes that the EDS deviation remains constant at its mid-point value for an entire segment duration (54·87 $\mu$s). In other words, the method assumes that the EDS is a symmetrical 669-step staircase rather than a continuous linear signal (there are 669 time segments in one frame, owing to overlapping). As a result, the effect of the EDS on the RF spectrum of each individual segment can be considered as a shift in centre frequency of the spectrum. Thus, the frequencies of the RF spectral segments are each shifted by a different amount determined by the time instant of the segment. The computation time required for this approach virtually does not depend on the number of EDSs simulated. However, the error associated with staircase EDS increases with the peak-to-peak deviation due to EDS. It is found that the error is about $\pm 1$ dB if the carrier is modulated by the 4 MHz peak-to-peak deviation EDS alone. Note that the dithering effect of higher frequency, random video modulation will practically eliminate any error associated with the staircase EDS approximation.

## 5. GENERATION OF FDM/FM POWER SPECTRA

Two alternatives exist for the generation of FDM/FM power spectra, namely the Gaussian approximation[3] or the white noise loading test (a simulation approach).[4,5] Both approaches are inaccurate for low-capacity carriers (e.g. a 72 channel carrier). However, the latter does reflect conventional NPR test methods and is used in this study.

*Simulation of FDM/FM power spectrum*

In this approach, the FDM/FM carrier power spectrum is generated by frequency modulating the carrier by a simulated baseband FDM telephony signal. The baseband signal is simulated by a number of equal-amplitude, randomly-phased sinusoidal tones. Each of these tones can represent one or more telephone channels. In order to limit FFT size, a maximum of 2048 samples is used to represent the FDM/FM signal. For larger simulation bandwidths this requires decreased frequency resolution. For example, for the set consisting of 60 telephone channels, 60 sinusoidal tones located 4 kHz apart are used. In this case, each tone represents one telephone channel. On the other hand, 252 telephone channels are modelled as 126 sinusoidal tones located 8 kHz apart, each representing 2 telephone channels. The baseband picowatt interference power, however, in all cases is calculated for a bandwidth of 3·1 kHz.

## 6. CALCULATION OF FDM BASEBAND INTERFERENCE BY CONVOLUTION OF RF SPECTRA

It can be shown that, for low interference conditions, (following reference 6) the baseband interference power spectrum $I(f)$ at the output of an FM demodulator with de-emphasis is given by:

$$I(f)=\frac{f^2}{|H_p(f)|^2}\frac{1}{4A_s^2} \times [S_{V_i} * S_{\nu_s}(f-f_s)+S_{V_i} * S_{\nu_s}(-f-f_s)] \quad (1)$$

where

- $H_p(f)$ is the voltage transfer function of the pre-emphasis network
- $A_s$ is the amplitude of the wanted signal
- $S_{V_i}$ is the lowpass equivalent power spectrum of the (arbitrary) interfering RF signal
- $S_{\nu_s}$ is the lowpass equivalent power spectrum of the wanted RF signal (normalized to unit power)
- $f_s$ is the frequency separation between the wanted and interfering carriers
- $*$ denotes convolution.

If the interfering signal is also angle modulated (i.e. constant envelope), the baseband interference spectrum can be written in terms of the normalized RF spectral densities and the wanted-to-total interference power $C/I$ as follows:

$$I(f)=\frac{f^2}{4\left(\frac{C}{I}\right)|H_p(f)|^2} \times [S_{\nu_i} * S_{\nu_s}(f-f_s)+S_{\nu_i} * S_{\nu_s}(-f-f_s)] \quad (2)$$

where $S_{\nu_i}(f)$ and $S_{\nu_s}(f)$ are the lowpass equivalent spectral densities of the interfering and wanted RF signal, respectively (both are normalized to unit power).

Equation (2) gives the interference power spectral density in units of $Hz^2$ of deviation per Hz of bandwidth. The unweighted signal-to-interference

ratio $S/I$ of a baseband telephone channel centred at $f_c$ is calculated by

$$\frac{S}{I} = \frac{(\Delta f_{TT})^2}{2\int_{f_c-b/2}^{f_c+b/2} I(f)\,df} \tag{3}$$

where

$\Delta f_{TT}$ is the r.m.s. frequency deviation for a 0 dBM0 test tone

$b$ is the bandwidth of a telephone channel (3·1 kHz).

The factor of 2 appearing in front of the integration sign is needed since $I(f)$ is a double-sided spectrum. The interference power in picowatts is given by

$$I(\mathrm{pW}) = \frac{10^9}{\left(\frac{S}{I}\right)} \text{ (unweighted)} \tag{4}$$

If psophometric weighting is used, (4) becomes

$$I(\mathrm{pWp0}) = \frac{5{\cdot}623 \times 10^8}{\left(\frac{S}{I}\right)} \text{ (psophometric weighted)} \tag{5}$$

## 7. MEASUREMENT RESULTS

Some sample plots of the results are presented in this section. These include two sample plots of FMTV power spectra; two FMTV spectral masks exceeded for 0·1 and 90·0 per cent of the time—one without addition of EDS, one with 4 MHz peak-to-peak deviation EDS; and a plot of worst-channel interference power distribution for the 792-channel FDM/FM carrier.

The results were computed for 15 MHz peak-to-peak picture deviation, co-channel interference (i.e. same carrier centre frequencies), and carrier-to-total interference power ratio of 20 dB.

### *FMTV spectra*

The FMTV power spectra of a split-field 75 per cent colour bar frame and a typical news programme frame are shown in Figure 4. Visual inspection of spectra of about 100 off-air frames produced the following observations:

(i) Lower-frequency sides of most FMTV spectra are very similar. This is because all TV frames have the same systematic signals (sync pulses and colour burst) and most of them are not saturated (in colour) and are positively biased.

(ii) The shape of the FMTV spectrum can be roughly predicted from the colour contents of the frame. Uniform pictures will probably cause the spectrum to concentrate at a certain frequency, whereas pictures with many details will cause the spectral density to spread out over a frequency band.

(iii) The −40 dB bandwidth of the majority of FMTV spectra without EDS is 15 MHz.

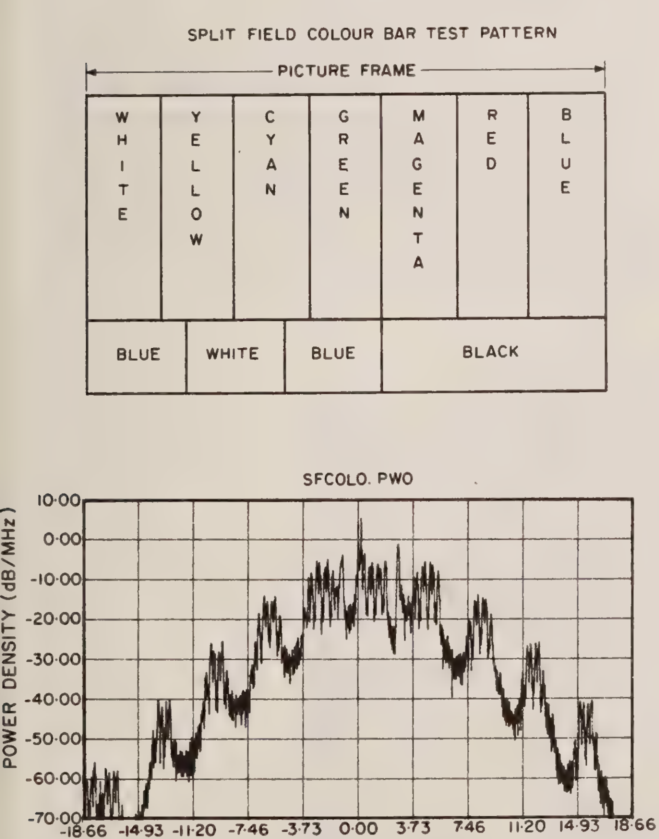


Figure 4(a). Spectra for split-field 75 per cent colour bar test pattern

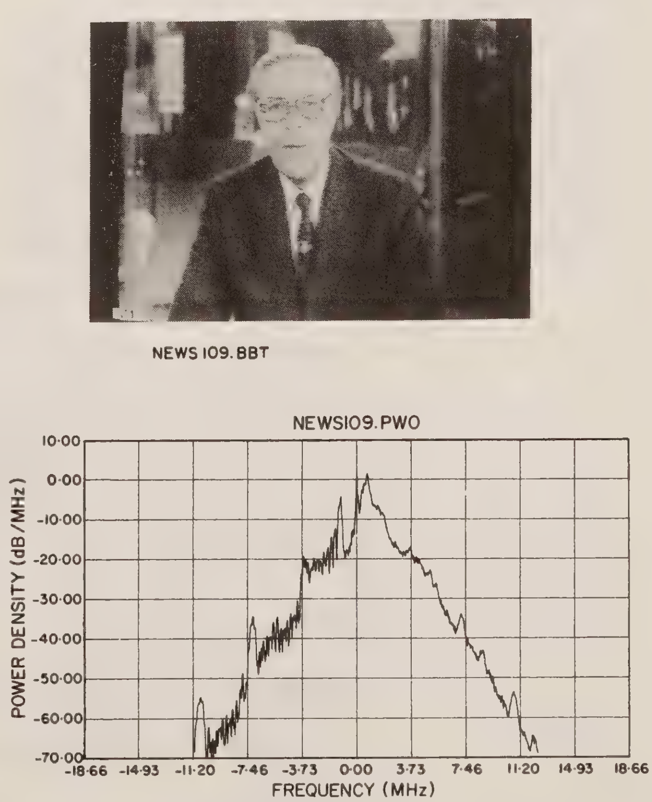


Figure 4(b). Spectra for a typical news programme picture frame

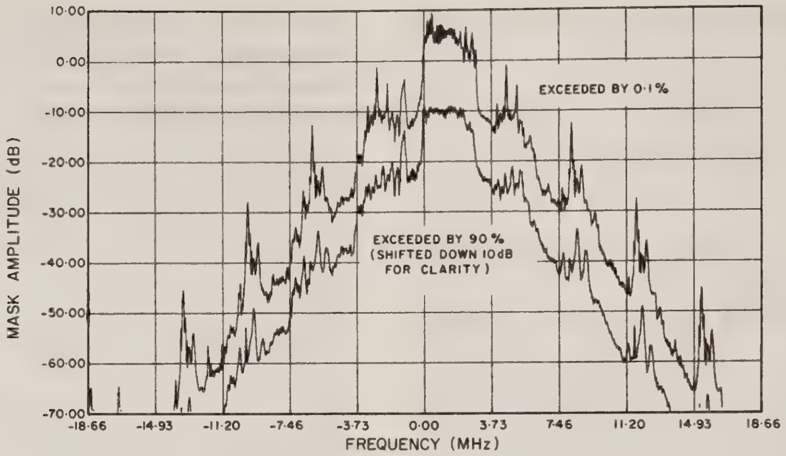


Figure 5(a). FMTV spectral mask (no EDS)

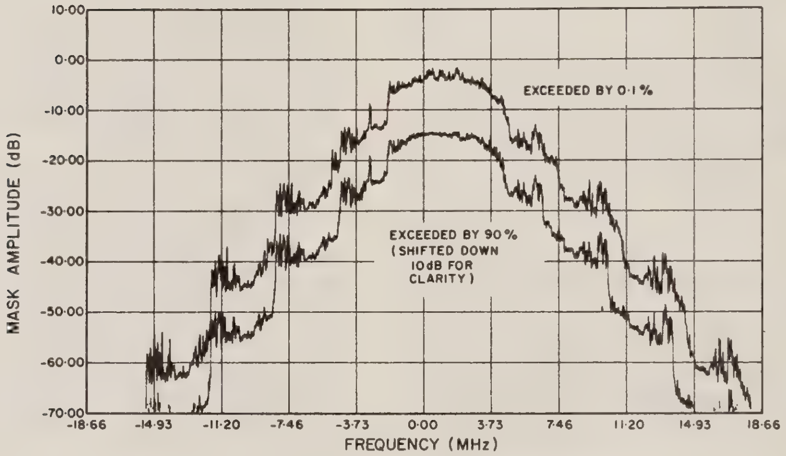


Figure 5(b). FMTV spectral mask (4 MHz EDS added)

*FMTV spectral mask*

The FMTV spectral masks are derived from the spectra of 1000 off-air TV frames as follows: the 1000 FMTV spectra are sorted so that their peak values are in descending order; the mask exceeded for $x$ per cent of the time is the envelope of the last $(100-x)$ per cent of the ordered spectra. For example, the mask exceeded for 10 per cent of the time will be the envelope of the 900 FMTV spectra having lowest peak power densities. Note that the masks computed this way contain minimum energy.

Figure 5 shows the FMTV spectral masks, without and with 4 MHz peak-to-peak deviation EDS, exceeded for 0·1 and 90 per cent of the time. Note that the tightness of the masks increases with the peak-to-peak deviation due to EDS.

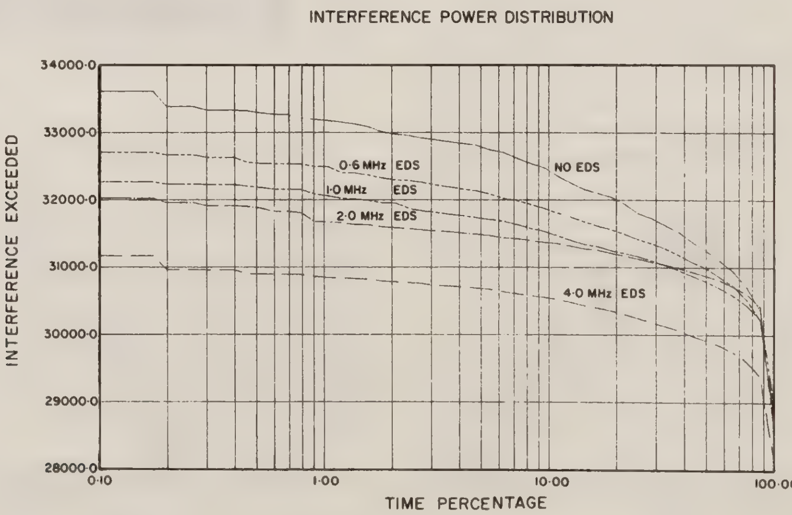


Figure 6. Baseband interference power in pWp0 exceeded versus time percentage for FDM/FM carrier (792 channels) for various EDS peak-to-peak deviations

*FDM baseband interference*

Figure 6 shows the plots of worst-channel FDM interference power level in pWp0 (psophometrically weighted picowatts) exceeded versus time percentage without and with 0·6 MHz, 1·0 MHz, 2·0 MHz and 4·0 MHz peak-to-peak deviation EDSs. Note that the curve for 2 MHz EDS crosses those for lower EDS deviations at the far right of the plot. This suggests that addition of EDS does not always reduce the interference level into the basebands of FDM/FM carriers. However, the interference enhancement is small and occurs for only a small percentage of time.

## 8. CONCLUSION

In this paper, a system which measures the TV interference into basebands of FDM/FM carriers has been outlined. The 'measurement' involves computation of FMTV power spectra from off-air collected TV frames and convolution of the interfering FMTV and wanted FDM/FM power spectra to produce the interference spectrum into the baseband of the wanted signal. Apart from the collection of off-air TV signal samples, all processing is performed in software. This includes computation of FMTV and FDM/FM power spectra and computation of FDM baseband interference by convolution of RF spectra. The programs are flexible enough to be used for video formats other than NTSC with only slight modifications. Time statistics which are in the form of FMTV spectral masks and worst-channel FDM baseband interference power distributions have been derived from measured data of 1000 off-air TV frames using this system. These statistical results are useful in predicting the interference level into FDM/FM carriers from TV signals. The FMTV spectral masks can also be used to predict the worst-case interference level into narrowband carriers.

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# THE VARIABILITY OF THE IONOSPHERIC TOTAL ELECTRON CONTENT AND ITS EFFECT ON SATELLITE MICROWAVE COMMUNICATIONS*

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## SUMMARY

Rotation of linearly polarized waves (Faraday rotation) passing through the ionosphere causes depolarization in frequency reuse satellite communication systems. As the ionospheric total electron content (TEC) is not constant, dynamic compensation for this effect may be required. This paper investigates the magnitude of the TEC variations, the time scales of the variability and the predictability of the excursions. Analysis of long-term TEC measurements shows that the variations are statistical with yearly and seasonal trends strongly coupled to long term solar and geophysical effects. Short-term variations are difficult to predict. Data indicate that reliable Faraday rotation estimates can be made for 99·9 per cent of the time, provided that long-term solar, seasonal and geographical factors are considered. Occasional bursts of solar activity limit the accuracy of long-term predictions.

KEY WORDS Faraday rotation Depolarization Ionosphere

## 1. INTRODUCTION

The polarization of a linearly polarized plane wave passing through the earth's ionosphere experiences a rotation proportional to the total electron content (TEC). This is known as Faraday rotation and may be a significant problem for frequency reuse in linearly polarized satellite communication systems.[1] Faraday rotation can be compensated for by rotating the transmit and receive feeds in the earth-station antennas. The need for compensation depends on both the magnitude of the Faraday rotation and the vulnerability of the communication system to the associated degradation due to cross-polarization interference. Since the amount of Faraday rotation is directly proportional to TEC, the cross-polarization level follows the behaviour of the TEC. The purpose of this paper is to examine available TEC data to derive the extent of both its temporal and spatial variability.

Previous compilations and analyses of TEC data have focused primarily on the behaviour of the mean value and its relation to other solar-geophysical parameters, such as solar activity or geomagnetic indices. Although these results are generally useful, mean values are not sufficient for predicting the magnitude and extent of extreme situations, such as the percentage of time that a particular level of TEC is exceeded. As with rain attenuation, terrestrial interference, and other factors contributing to transmission degradation, a statistical distribution of TEC levels is required for estimating system performance and predicting outages. In the following sections, available TEC data are analysed to obtain a statistical distribution of TEC levels. Diurnal, seasonal and long-term variability are discussed. The dependence of TEC on latitude is presented. Correlations of mean and extreme TEC levels with solar activity are considered. Results are presented in graphical form indicating the percentage of time that TEC exceeds a specified level. A companion paper,[2] to be published in a future issue of the *International Journal of Satellite Communications*, compares measured depolarization data with predictions based on solar activity and other geophysical factors. Methods of mitigating depolarization by antenna feed rotation are assessed.

## 2. AVAILABLE TEC DATA

TEC is measured primarily by monitoring the Faraday rotation of electromagnetic waves passing through the ionosphere. The observed rotation $\Theta_F$ is converted to TEC by inverting the integral

$$\Theta_F = \frac{C}{f^2}\int_0^H N_e \mathbf{B}\cdot \mathbf{d}l \qquad (1)$$

where $\mathbf{B}$ is the geomagnetic field, $N_e$ is the electron density, $f$ is the frequency, $\mathbf{d}l$ is the wave path and $C$ is a constant. Ideally, the signal source is in geostationary orbit and the measurements are made continuously. The first TEC measurements reported were made by observing low altitude satellites[3,4] in the late 1950s and by reflecting radio signals from the moon.[5–7] These data are of limited value for statistical considerations as the measurements were not continuous, but they are useful in noting general trends. Available published results are summarized in Table I. In Section 5 the principal results of these measurements will be compared

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Table I. Sources of primary TEC data

| Reference | Period covered | Site | Type of coverage | Method used |
|---|---|---|---|---|
| 1 | October 1955–October 1956 | Jodrell Bank, U.K. | Discontinuous | Moon bounce of radio signals |
| 2 | June 1958–November 1958 | Belmar, NJ, U.S.A. | 2 days in June 3 days in November | Moon bounce of radio signals |
| 3 | September 1958–April 1959 | Palo Alto, CA, U.S.A. | Successive passages | Low altitude satellite (Sputnik II) |
| 5 | January–February 1960 | Jodrell Bank, U.K. | Discontinuous | Moon bounce of radio signals |
| 6 | May–August 1960 December 1960–February 1961 April–August 1961 | Auckland, New Zealand | Successive passages | Low altitude satellite (Explorer 7) |
| 7 | November 1967–September 1973 | Sagamore Hill, MA, U.S.A. | Continuous hourly measurements | Geosynchronous satellite (ATS-3) |
| 8 | December 1967–December 1973 | Urbana, IL, U.S.A. | Continuous half-hourly measurements | Geosynchronous satellite (ATS-3) |
| 9 | January 1968–December 1968 | Sagamore Hill, MA, U.S.A. | Monthly means of each hour | Geosynchronous satellite (ATS-3) |
| 10 | December 1971 | Northern Hemisphere Multistation, 70°W | Continuous daily medians | Geosynchronous satellite (ATS-3) |
| 11 | July 1974–May 1975 | Boulder, Colorado, U.S.A. | Continuous hourly measurements | Geosynchronous satellite (ATS-6) |
| 12 | Current, real time | Multistation, world-wide | Continuous hourly measurements | Geosynchronous satellite (ATS-5, GOES) |

with data from more recent epochs to infer long-term variability.

The launching of geostationary satellites beginning in the 1960s has provided a means of obtaining continuous long-term TEC observations. Signals from the ATS-3 and ATS-6 satellites[8–10] at 150 MHz have been monitored by several observers for extended periods and these data have proved useful in obtaining statistical distributions of TEC. Gradients in TEC have been established from data obtained simultaneously from networks of receiving stations observing the same satellite.[11] Current values of TEC are available in real time through the Space Environment Laboratory of the National Oceanic and Atmospheric Administration.[12] Data from nine world-wide observatories are compiled and made available by computer terminal through the Space Environment Laboratory Data Acquisition and Display System (SELDADS).

Data for this statistical study were selected primarily from two sources: observations of ATS-3 geostationary satellite signals made at Urbana, Illinois[10] between 1 December 1967 and 30 December 1970; and observations of the ATS-5 geostationary satellite made at Sagamore Hill, Massachusetts[12,13] from 1 March to 31 May 1979. The selection was motivated by the following considerations:

1. Both data sets span time intervals of maximum or near maximum solar activity and therefore maximum TEC.
2. The data are virtually complete, with minor gaps.
3. The data were taken with geostationary satellites as the signal source, ensuring a constant path through the ionosphere.
4. The observing sites are located within the continental United States and thus the results are directly applicable to mid-latitude earth-station sites.
5. The data are presented as hourly values for each day and can be readily used for statistical analysis.

## 3. DATA ANALYSIS

The TEC data were initially analysed on a monthly basis to preserve seasonal variability from the averaging effects of larger ensembles. The Sagamore Hill data, although in principle equivalent to the SELDADS real-time data, were subjected to additional scrutiny to remove instrumental irregularities.[12,13] TEC values for each hour of each month examined were sorted into equally spaced intervals to establish the time per month during which the TEC fell in each range. The overall range was from 0 to 100 ($\times 10^{16}$) electrons $m^{-2}$ in a vertical column and was divided into intervals of $5 \times 10^{16}$ (subsequently, the multiplier $10^{16}$ will be deleted and a TEC unit defined in terms of $10^{16}$ electrons $m^{-2}$ will be used). The Urbana data were analysed for March, June, September and December of each year available, as previous studies of mean variability have shown that TEC is typically maximum in March and September and minimum in June.[14] The Sagamore Hill data were analysed for the three months available.

Statistical distributions of the percentage time (per month) in which the TEC exceeded a given value were obtained by summing over the appropriate ranges and dividing by the total time considered. Results for Urbana and Sagamore Hill are presented graphically in Figures 1(a)–(c), and 2. TEC levels exceeded for any percentage of time can be obtained from these graphs.

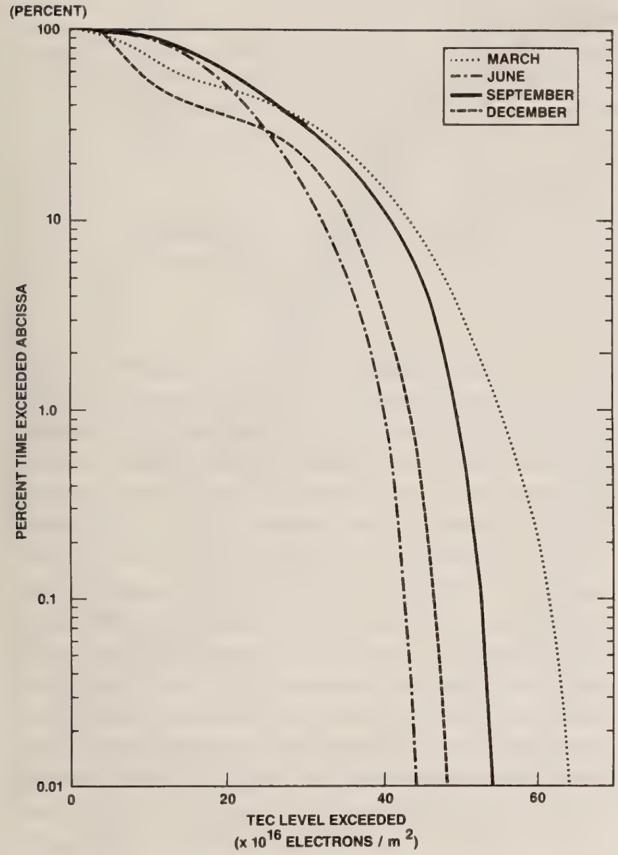


Figure 1(a). Monthly cumulative distributions of percentage time that TEC exceeded levels shown; 1968 Urbana data

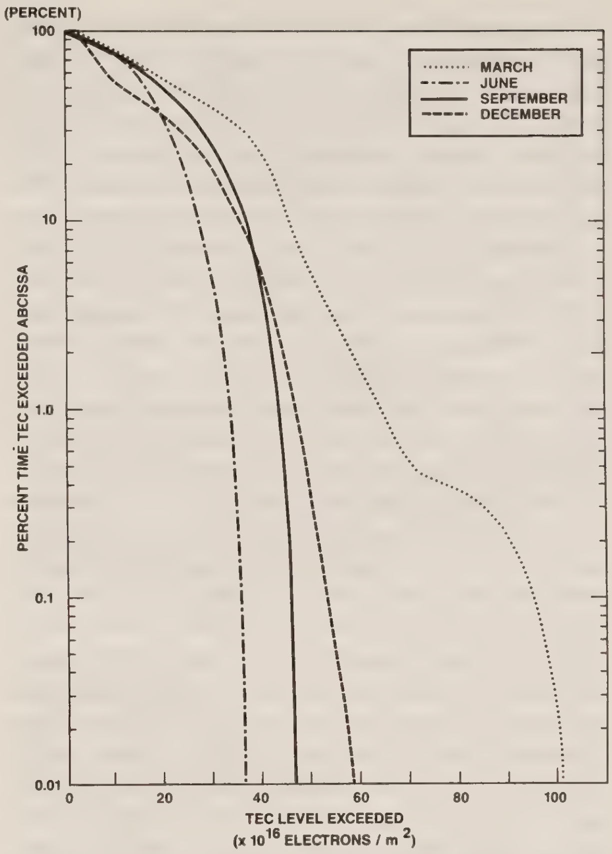


Figure 1(c). Monthly cumulative distributions of percentage time that TEC exceeded levels shown; 1970 Urbana data

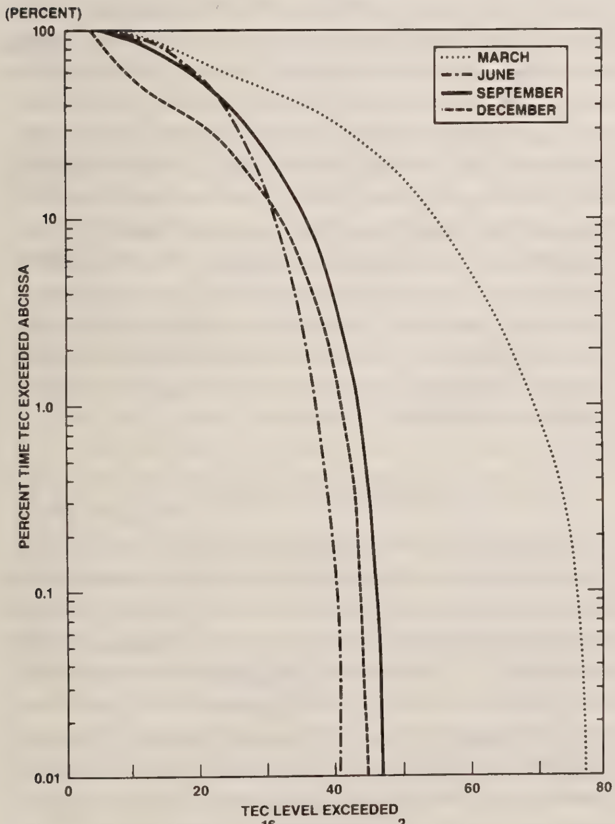


Figure 1(b). Monthly cumulative distributions of percentage time that TEC exceeded levels shown; 1969 Urbana data

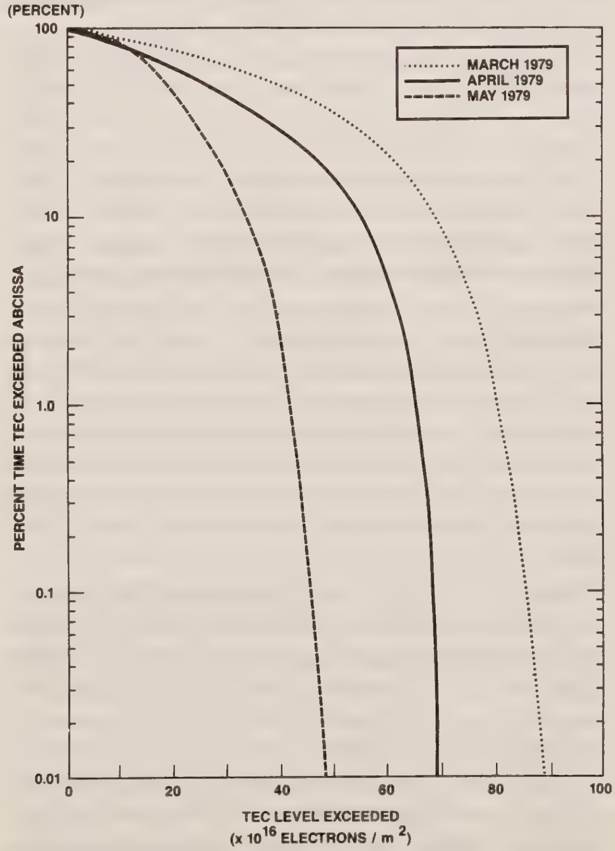


Figure 2. Monthly cumulative distributions of percentage time that TEC exceeded levels shown; 1979 Sagamore Hill data

These data show several important results. Seasonal variability is readily apparent in the Urbana data, where the maxima in TEC consistently occur in March of each year and the minima in June, as had been shown previously for the means.[14] The Sagamore Hill data exhibit the same tendency. The year-to-year variability for a particular month is not as systematic. The TEC level exceeded 1 per cent of the time increased for March between 1968 and 1970, but decreased for December, September and June. With the exception of June, the changes were not monotonic. March 1969, for example, was a maximum for the three years, whereas September 1969 was a minimum. The correlation of these trends with solar activity is discussed in Section 4.

Comparison of the Sagamore Hill 1979 data with the Urbana 1967 and 1970 data on a month-to-month basis shows a major difference. At the 1 per cent level the average of the March 1968, 1969 and 1970 TEC levels is 62 for Urbana, whereas in March 1979 at Sagamore Hill it was at 80, 30 per cent higher. As discussed below, this difference is attributed to both the geographical difference due to location and the temporal effect of different solar cycles. It has been previously noted that mean TEC levels can be well correlated with sunspot numbers[14,15] (a measure of solar activity) and that they are also strongly influenced by latitude difference.[11] Data taken at Sagamore Hill in 1968 have been reported[15] in a format of hourly means, 10, 25, 75 and 90 per cent levels on a monthly basis, which can be used to derive an estimate of the percentage time exceeded at various levels.

Sagamore Hill data for two months in 1968, March and June, were analysed and the results show a 17 per cent lower TEC level at the 1 per cent point in March and a 28 per cent lower level in June from Sagamore Hill relative to Urbana. This trend is consistent with simultaneous multi-station TEC measurements made in 1971, where it was shown that daytime TEC levels increased with decreasing latitude, corresponding to greater solar illumination of the ionosphere.[11] At the latitudes of the Urbana and Sagamore Hill stations (40°N and 42·5°N), the difference in the monthly mean TEC was typically 18 per cent at the hour of maximum TEC. The increase in extreme TEC level with decreasing latitude, shown in the results of this study for March and June 1968, follow the same trend.

The effect of solar cycle on extreme TEC level is seen in the comparison of March 1968 and March 1979 data from Sagamore Hill. At the 1 per cent point, the March 1979 level exceeded is 78 per cent greater than in March 1968. This behaviour is discussed further in Section 4.

Yearly behaviour of TEC level exceeded for percentage time was obtained by combining the monthly Urbana data. These results are approximate in so far as the four months of data per year were used to represent the remainder of the time.

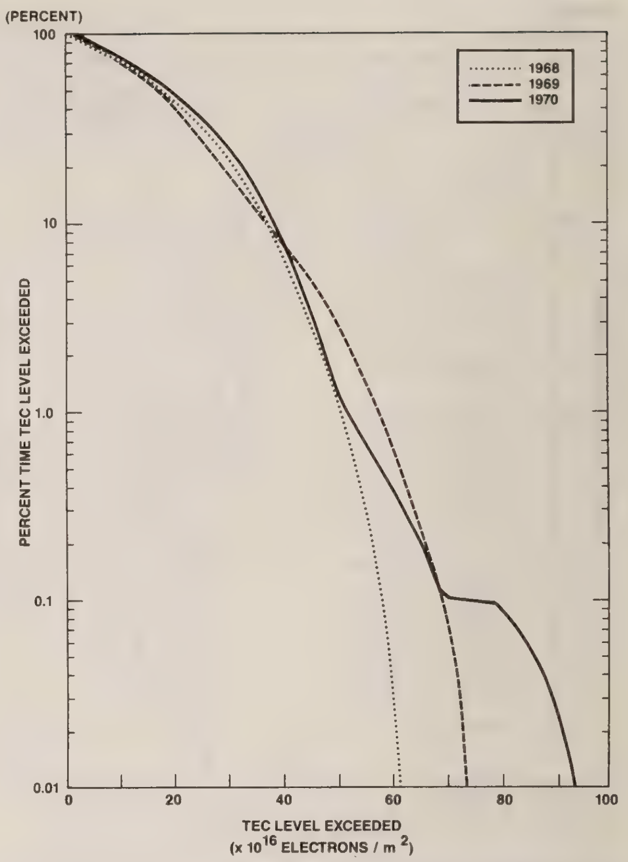


Figure 3. Yearly cumulative distributions of percentage time that TEC exceeded levels shown; 1968–1970 Urbana data

(For instance, results for March were assumed to be valid for February to April.) The results are presented graphically in Figure 3. The curve for 1970 diverges radically from the other two shown, owing to a single day of enhanced solar activity (8 March) in which the TEC exceeded 90 for two hours. Because of the approximation described above, this particular event has been given excess statistical weight. Examination of data for all days in 1970 showed no other examples in which the TEC exceeded 70. The curves in Figure 3 are therefore conservative, tending to overestimate the percentage time that TEC exceeds the highest levels (for the 1970 case, the results could be scaled by dividing the percentage time exceeded for TEC values greater than 70 by 3).

## 4. TEC VARIABILITY AND SOLAR CYCLE

The relationship between mean TEC level and solar activity has been extensively studied, resulting in the general conclusion that long-term average measures of solar activity are well correlated with mean TEC.[16] In a study of Sagamore Hill TEC data for November 1967 to December 1976, the correlation between the 12 month average sunspot number, $\bar{R}$, and 12 month average hourly TEC, $\bar{I}$, was found to be very good. The correlation coefficient reached 0·94 for hours of peak TEC.[14] For monthly averages of the same quantities, the correlation was found to be weak. The correlation of $\bar{R}$

Table II. Mean and extreme TEC levels

| Observing station | Year | Mean TEC | TEC level exceeded 1% | 1% level mean | TEC level exceeded 0·1% | 0·1% mean level |
|---|---|---|---|---|---|---|
| Urbana | 1968 | 22·2 | 51 | 2·3 | 58 | 2·6 |
| | 1969 | 22·8 | 53 | 2·3 | 69 | 3·0 |
| | 1970 | 19·6 | 52 | 2·6 | 65 | 3·3 |
| Boulder | 1974–1975 | 12·0 | 32 | 2·6 | 46 | 3·8 |

and $\bar{I}$ remained strong for a wide range of solar activity, although at solar minimum (small sunspot number) a divergence from linearity was noted. Similar correlation of mean TEC with solar microwave radio flux (2·8 GHz) has also been observed.[15,16] The correlation between sunspot number and mean TEC would be useful in predicting extreme TEC levels, if it could be shown that mean and maximum TEC are also well related. Solar activity is generally low near the minimum in the solar cycle, but occasional bursts of energetic events may occur in the years following the maximum sunspot number, contributing to a brief interval of high TEC but having little effects on the mean. Only 8·76 hours of unusually high TEC are required to exceed the 0·1 per cent level on a yearly basis.

The relationship between mean and extreme TEC was examined further by comparing the yearly mean TEC value with the TEC levels exceeded 1 per cent and 0·1 per cent in that year. Data obtained at Urbana[10] near solar maximum (1968 to 1970) and measurements made at Boulder[6] (1974 to 1975) were used for the comparisons. The ratios of TEC level exceeded for 1 per cent and 0·1 per cent of the year to yearly mean were used as a measure of the correlation. Results are shown in Table II. At the 1 per cent of time exceeded level, the results for solar maximum and minimum are similar: the ratio is a mean of 2·5 with a 12 per cent spread. At the 0·1 per cent of time exceeded level, the trend is different. The ratio at solar minimum (1974 to 1975) is greater than for solar maximum. Furthermore, the ratios show a 37 per cent variability over the 4 years considered. Examination of the raw data showed that the variability was in each instance due to one or two days of extreme TEC levels per year.

Previous efforts had shown poor correlation between monthly mean sunspot number $\bar{R}_m$ and monthly mean TEC level,[14] and a similar comparison of $\bar{R}_m$ with extreme TEC level yields similar results. A regression of $\bar{R}_m$ against TEC level exceeded 1 per cent of the time for monthly data between December 1967 and December 1970 (Urbana) produced a regression coefficient of 0·39; a measure of poor correlation. Similar analysis of 1979 Sagamore Hill data gave the same conclusion; that the current mean sunspot number and extreme TEC level are not well correlated.

## 5. DISCUSSION

Commercial satellite communication systems predominantly use frequency bands at 6 and 4 GHz. For typical values of the quantities in equation (1), the Faraday rotation ranges from almost zero to 5°. For linearly polarized systems, the corresponding depolarization (XPD), given by

$$\mathrm{XPD} = 20 \log \tan \Theta_F \qquad (2)$$

may cause significant impairment to the communication channel for extreme values of $\Theta_F$. Owing to the frequency dependence of the Faraday effect, rotation is negligible in the higher satellite bands (14/11 GHz and 28/19 GHz). The analysis in the previous sections has provided a set of curves of the statistical distribution of TEC level versus percentage time the level was exceeded. Before these results can be used to estimate Faraday rotation, several factors require further consideration. Since Faraday rotation angle $\Theta_F$ is proportional to TEC (equation (1)), the change in rotation angle, $\Delta\Theta_F$ will be proportional to the change in TEC. For earth-station performance considerations, the latter quantity,

$$\Delta\mathrm{TEC} = \mathrm{TEC}_{MAX} - \mathrm{TEC}_{MIN} \qquad (3)$$

is the appropriate parameter to use in predicting cross-polarization levels. Ideally the antenna feed system could be set midway between $\Theta_{MAX}$ and $\Theta_{MIN}$, and the maximum angular excursion would be reduced to $\frac{1}{2}\Delta\Theta_F$.

The TEC is modulated strongly on a daily basis by solar illumination of the ionosphere. Night-time TEC levels are depleted primarily by electron recombination and sustained by diffusion processes.[14] Evidence indicates that recombination is dominant as the minimum level is attained just before dawn. This behaviour was examined statistically by correlating $\Delta$TEC with $\mathrm{TEC}_{MAX}$ for several months under different solar activity conditions. The results showed strong correlation regardless of the maximum TEC level attained. The linear relationship

$$\Delta\mathrm{TEC} = \mathrm{TEC}_0 + M\,\mathrm{TEC}_{MAX} \qquad (4)$$

is plotted in Figures 4(a) and 4(b) for two months of high and low $\mathrm{TEC}_{MAX}$. Correlation coefficient $r$, slope $M$ and intercept $\mathrm{TEC}_0$ for these and other months considered are given in Table III. In all cases, the correlation is excellent ($r \sim 1$) and the slopes and intercepts are in good agreement. These

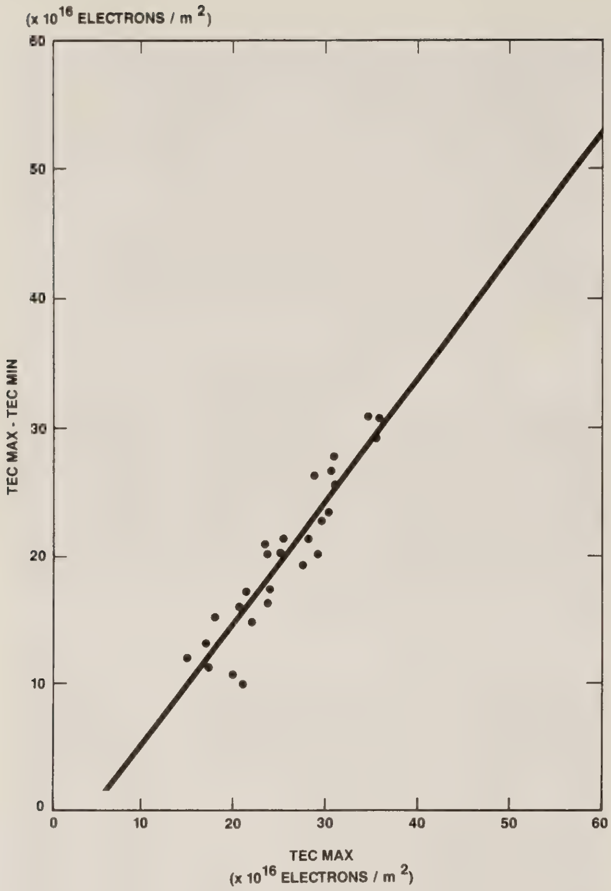


Figure 4(a). Linear regression of $TEC_{MAX}-TEC_{MIN}$ against $TEC_{MAX}$ for a month of low solar activity

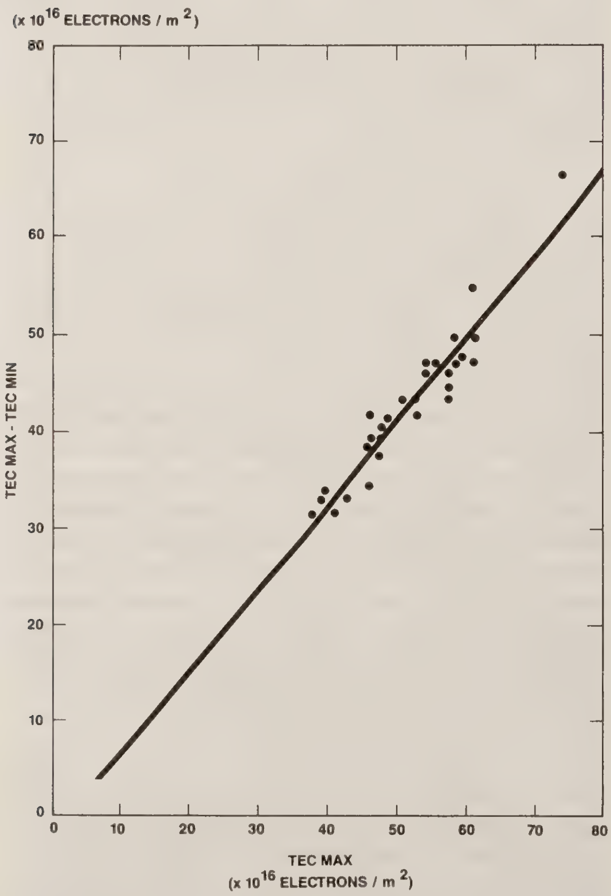


Figure 4(b). Linear regression of $TEC_{MAX}-TEC_{MIN}$ against $TEC_{MAX}$ for a month of high solar activity

Table III. Regression of $TEC_{MAX}$ against $TEC_{MAX}-TEC_{MIN}$ $TEC_{MAX}=TEC_0+M(TEC_{MAX}-TEC_{MIN})$

| Data (month, year) | $TEC_0$ | $M$ | Regression coefficient, $r$ |
|---|---|---|---|
| Sagamore Hill | | | |
| March 1979 | 3·93 | 0·91 | 0·95 |
| Urbana | | | |
| December 1967 | 2·97 | 0·99 | 1·00 |
| March 1970 | 2·28 | 0·86 | 0·96 |
| June 1970 | 4·33 | 0·95 | 0·94 |

results imply that the night-time minimum TEC is small and independent of daytime maximum. Since the Faraday rotation at minimum TEC would be negligible the behaviour of $TEC_{MAX}$ is a good predictor of $\Delta\Theta_F$.

As TEC exhibits daily, seasonal and solar cycle modulated variability, the utility of the distributions presented in this study is determined by the similarity of the conditions when the TEC data were obtained to the time period in which the application is intended. Solar activity exhibits a fundamental 11 years periodicity with the mean sunspot number $\bar{R}$ serving as a convenient indicator. Cycle to cycle variability is marked, and in the past three cycles, the mean annual values of $\bar{R}$ at solar maximum have differed by almost[15] a factor of two. The long term behaviour[17] of $\bar{R}$ (365 years) shows intervals where sunspot activity virtually vanished.

As mean $\overline{TEC}$ and $\bar{R}$ are well correlated, direct estimates of the former can be obtained from predictions of the latter. Various methods of predicting $\bar{R}$ have evolved, using either previous values of $\bar{R}$ to predict trends[18,19] or other geomagnetic indicators as precursors.[20,21] To the extent that $\overline{TEC}$ and TEC extremes are related, the predictions of $\bar{R}$ establish a basis for estimating extreme TEC levels. As previously shown, variability at the 1 per cent of the time exceeded level is moderate but unrealiable at the 0·1 per cent level. As a rule of thumb the TEC level exceeded 1 per cent of the time (on a yearly basis) could be established by first deriving the mean $\bar{R}$ for the time interval of interest by one of the predictive techniques[18–21] and then obtaining $\overline{TEC}$ from its correlation with $\bar{R}$.[14,15] From Table II, TEC, 1 per cent $\cong 2{\cdot}6\times\overline{TEC}$.

On a shorter time scale, TEC variability is dominated by seasonal effects. As previously shown, maximum means and extremes for the northern hemisphere occur in March. This result is the combination of several factors: increased electron production due to the illumination of the northern hemisphere as the earth's inclination becomes more favourable and relatively low electron loss rate due to recombination with atmospheric constituents. In the summer months, the atmosphere expands due to heating and the rising $O^+$ and $N^+$ ions deplete the electron population, and the solar flux diminishes as the earth becomes more distant from the sun. These two effects outweigh the increase in

orbital inclination at the summer solstice, resulting in a TEC minimum in June.[15]

Consideration of geographical location should also be made before applying the results of this study to a particular situation. Previous studies of mean TEC values have shown strong gradients over the latitudes of the continental United States. In December 1971, the monthly mean hourly TEC maximum increased from[11] 20 at 42°N to 27 at 30°N. Examination of current real time TEC data obtained through SELDADS shows that Sagamore Hill measurements (42°N) are usually less than or equal to those of Boulder (40°N). Data from Ramey, Puerto Rico (18°N) are typically 75 to 100 per cent greater. This lattitude dependence must be considered to obtain $\Theta_F$ for a specific earth station and satellite, in accordance with equation (1).

## 6. CONCLUSIONS

The results of this study can be summarized in the following statements:

1. TEC and solar activity are well correlated: TEC is modulated by the 11-year solar cycle, seasonal and diurnal periods.
2. Extremes in TEC level are generally related to solar activity, but the percentage time that a particular level is exceeded becomes less predictable as smaller percentages of time are considered.
3. Predictions of Faraday rotation and subsequent cross-polarization interference can be made on the basis of these results, but caution should be exercised in estimating results for levels exceeded less than 1 per cent of the time.
4. Future long-term predictions of TEC are strongly influenced by solar maximum activity levels, which vary considerably from cycle to cycle. The current (1980) maximum is midway between the previous two, implying that current TEC values are probably indicative of the maximum to be expected for the next ten years, with the possible exception of a few hours per year.

A companion paper,[2] to be published in a future issue of the *International Journal of Satellite Communications*, treats the application of these findings to a 6/4 GHz satellite communications system. A method of predicting the magnitude of Faraday rotation, based on solar cycle data, will be presented and applied to stellite communications systems. The predictions are used to derive the percentage time that the XPD would exceed prescribed levels. The effectiveness of periodically adjusting the antenna feed orientation to minimize the depolarization is examined. Predictions are compared with depolarization measurements, and it will be shown that commonly acceptable levels of XPD can be obtained by relatively infrequent (e.g. annual) feed angle corrections.

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# COMMENTARY

## THE CASES **FOR** AND **AGAINST** DEREGULATING THE GLOBAL SATELLITE NETWORK

### FOR

**New Entrants Would Lower Prices**

DAVID J. MARKEY

*Assistant Secretary of Commerce for Communications and Information, U.S. Government*

PRESIDENT Reagan determined last November that the national interest would best be served by allowing privately owned United States satellite systems into international communications. For INTELSAT, the nonprofit communications cooperative that has provided the bulk of international communications for the last two decades, as well as the users of international communications, President Reagan's action and the likely emergence of private satellite systems signal the start of a promising era of greater competition and technological progress.

International communications, forecast to grow by more than 14 per cent in 1985, constitute perhaps the fastest growing component of the telecommunications industry. The services involved (video, data and voice transmissions in both the corporate and consumer sectors) are critical to a diversity of important United States interests—expanded foreign commerce and investment, greater American trade in services, foreign policy and an effective national defense.

INTELSAT, a consortium of 109 nations established in 1964, now handles about two-thirds of the world's international communications traffic. But several American companies have applied to the Federal Communications Commission to deploy new satellite systems separate from INTELSAT to provide intra-office video services and data and voice transmissions, chiefly on the heavily trafficked North Atlantic routes. Significantly, under the Administration's proposal, private companies would be barred from hooking into the public telephone system, which would discourage entry into the major markets of intercorporate communications and telephone calls between individuals.

In the next five years, international communications should experience rapid changes similar to those that have reshaped our domestic communications markets. All the key ingredients for such change are present—a dynamic technology coupled with proliferating demand for the communications services needed to facilitate new services, including electronic banking, intercontinental television and electronic mail. And, for the American business community especially, this more diverse and competitive international communications environment promises significant advantages.

Currently, it costs a minimum of more than $2700 an hour to transmit television programming from New York to London using the facilities of A.T.&T., the Communications Satellite Corporation, INTELSAT and British Telecom. Domestically, however, such service over a comparable distance relying on domestic satellites costs only about $790.

Similarly, the least costly international private line service between New York and London now sells for

### AGAINST

**The System Works, Don't Fix It**

RICHARD R. COLINO

*Director General and Chief Executive Officer of INTELSAT*

The winds of domestic deregulation are now blowing on intercontinental and transoceanic satellite communications, an arena that since 1964 has been the responsibility of INTELSAT, the global satellite communications organization created at the urging of the United States to bring an efficient and affordable commercial satellite telecommunications system to the world.

INTELSAT, a nonprofit cooperative of 109 nations, provides two-thirds of the world's telephone service, almost all international television transmission, most telex service, teleconferencing, and many kinds of data transmission. The United States investment in INTELSAT is through the Communications Satellite Corporation, a private-sector corporation, and therefore places no burden on the United States taxpayer.

The Reagan Administration recently gave policy guidelines to the Federal Communications Commission under which international satellite systems separate from INTELSAT could be authorized. Because the proposed systems are designed to serve only lucrative, high-volume routes, the United States initiative has raised grave concerns throughout the world about INTELSAT's ability to continue to provide low-cost services to all countries. INTELSAT's member governments and telecommunications authorities have been asking a simple question, 'Why?'

INTELSAT works on the principle of nondiscriminatory charges through systemwide rate averaging. Revenues from the high-volume routes, such as the North Atlantic, make it possible to provide cost-efficient service to and from the developing countries.

Allowing competing satellite systems serving only high-volume routes to divert traffic from the INTELSAT system would decrease the organization's revenues. There would be fewer circuits over which to average the system's costs. The inevitable result would be higher charges to all users, including the United States Government, and, ultimately, the degradation of the global system.

Introduction of separate systems could unleash uncontrollable forces. Once begun, the process could be irreversible. There are no regulatory, legislative, judicial or administrative mechanisms at the international level to make adjustments when the process goes awry. Moreover, since INTELSAT is required by treaty to charge the same price to all users for each service, we could not compete with the proposed separate systems unless the treaty were changed.

The INTELSAT treaty forbids any member nation from starting or allowing the operation of any satellite system that would cause substantial economic harm to INTELSAT. The proposed policy change, without prior demonstration that the other member nations will benefit,



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**FOR**—*cont'd*

about $3700 a month. One can obtain comparable service between New York and Los Angeles on a domestic satellite system for as low as $1150 a month. As with domestic television transmission service, the United States customer for domestic intracorporate private line service enjoys the advantage of several suppliers competing for his or her business. Internationally, the customer today is relegated to dealing with monopoly, sole-source suppliers.

For INTELSAT and its signatories—among whom are most of the public and quasi-public communications agencies, such as our Communications Satellite Corporation or British Telecom—new entry will provide a spur to cut prices and offer customers more responsive service. Reliance on competitive incentives for more efficient performance is consistent with trends toward 'privatization' of communications manifest in Britain, Canada and Japan.

Competitive challenges, moreover, hardly threaten to undermine the global INTELSAT system, as officials of INTELSAT claim they would. Far from fragile, INTELSAT today is an established organization enjoying a worldwide presence, a large fleet of advanced satellites and a management staff composed of skilled and experienced communications professionals. Under the President's determination, furthermore, only competition for new, customized international satellite services would be allowed. By far the majority of INTELSAT'S traffic and core revenues will thus remain off-limits to the new satellite competitors.

Today, no single organization, no matter how talented, dedicated or perceptive, can be reasonably expected to anticipate, much less fully satisfy, all user needs in a world telecommunications marketplace that is fast undergoing major changes. Allowing competition for new satellite services is the most promising means of assuring that all developing communications needs are promptly met.

Competitive change in a market long characterized by monopoly is usually disconcerting. But this change is evolutionary in nature, and United States policy is seeking to minimize problems that might arise from the ongoing transition to a more competitive international communications field.

Customers should be afforded the benefits of lower prices, more responsive service and broader choice. The Administration's policy adequately safeguards INTELSAT's essential services while permitting desirable private aerospace and communications initiatives to go forward. This, it seems to us, is in the best interests of the international community and the American user.

**AGAINST**—*cont'd*

threatens to politicize the organization, bringing about the very disharmony that INTELSAT is so proud to have avoided. Indeed, the issue has already created tensions between the United States and its partners, both industrialized and developing countries. The widespread concern is that a proliferation of systems, all competing for the high-volume routes, will lead to the unravelling of the global consensus established in 1964.

It has been asserted that consumers will benefit. But exactly who are these consumers? A handful of the largest corporations, primarily in the United States. Smaller consumers—individuals, businesses, and the less developed nations—will suffer.

It has been argued that competition will promote growth and technological innovation, creating new and more efficient telecommunications systems. Yet, from the 1965 launching of its first satellite, Early Bird, INTELSAT has been on the leading edge of satellite technology. Today, its 15-satellite system interconnects countries of strikingly different economic, social, cultural and political backgrounds. The INTELSAT VI satellite, to be launched next year, will have 170 times the capacity and seven times the lifetime of Early Bird—an efficiency increase of 1000 times.

It has also been claimed that INTELSAT's charges are too high. That isn't so. Dramatic technological advances have been more than matched by reduced prices. Adjusted for inflation, INTELSAT's telephone charge for 1985 is only about 5 per cent of what it was in 1965. Domestic satellite companies charge about $165 an hour for a coast-to-coast telecast. The INTELSAT charge for a comparable International transmission is $68.40. The INTELSAT portion of a three-minute, $4.73 call between New York and Frankfurt is just over 50 cents—a little more than 10 per cent of the total charge.

If the problem is with the total cost of service to the user, why focus on INTELSAT's 10 per cent, rather than the remaining 90 per cent of the charge that is controlled by the Federal Communications Commission?

The world partners of the United States in INTELSAT question whether it makes sense to inject purely domestic regulatory concepts into the international arena. They ask why the burden has not been placed on those proposing such a fundamental change to make a persuasive showing that the possible benefits are worth the risk of irreparable harm to a unique global enterprise that serves the world's satellite communications needs so well.

These are fundamental questions. They have been asked for almost two years by the member nations that have invested in INTELSAT, and by the 60 other nations and territories that depend on the cooperative. The questions have not been answered.

The worldwide attitude concerning INTELSAT is, 'If it works don't fix it'.

And INTELSAT works.

# BOOK REVIEWS

Yearbooks and directories are only as good as the latest edition in print. They are usually updated annually and sometimes more frequently with updates during the year. Their value is in maintaining as current an information source as possible. The yearbooks reviewed below cover satellite communications and provide a wealth of information for the type of current data one needs quickly.

*Cable & Satellite Europe Yearbook 1985*. Published annually as a supplement to the *Cable & Satellite Europe* magazine, London, U.K. Editor-in-chief: Colin McGhee.

This is the first edition of the yearbook compiled by the staff of *Cable & Satellite Europe* magazine which started publication in 1984. The intent was to produce 'the most up to date and comprehensive guide to this industry', which covers the converging technologies of television, cable, satellites, telecommunication, teleconferencing and video.

The yearbook starts with the international scene—each chapter is preceded by a summary of events that occurred in 1984 and forecast for 1985 followed by a list of the names, addresses and phone numbers of contact persons in the telecommunication agencies involved. Emphasis is on the European scene, in the areas of communication satellites, DBS and programmes.

The main part of the yearbook covers descriptions of each European country's telecommunication system followed by names, addresses and contact persons. Each listing includes a country's government and regulatory agency, trade organization, TV broadcasting, telecom agency, cable, satellite hardware, programme channels, producers, facilities and consultants.

The positive aspect of this yearbook is the clear and succinct presentation of information about agencies that are often difficult to find. The list of telecommunication consultants in each country, for example, can be very useful. A drawback is the lack of an index; thus if one were looking for an address of a consultant or agency, one should first know in which country it is located. It is hoped that this inconvenience will be corrected with the upcoming 1986 edition. This drawback is minor compared to the wealth of information contained in the volume.

*Telecom Factbook 1985*. Published by TV Digest, Washington D.C., U.S.A., 1985.

Unlike *Cable & Satellite Europe Yearbook* this directory starts off with an index of all the agencies that are listed. Chapters include communication carriers, satellites, electronic mail, regulatory agencies, associations and international. Emphasis is on the United States, although other national agencies are represented in the International section.

This directory, if kept current, should prove useful as a contact source. Organizational breakdowns, sometimes with organigrams included, are listed to the secondary level of management titles. There is no name index however.

*Satellite Directory*. 7th edn, Phillips Pub, Bethesda, MD, U.S.A., 1985.

Probably the oldest of the directories 'a comprehensive guide to this rapidly changing industry'. Originally published as a guide to the North American satellite industry, it has expanded its scope to include international activities. There are indexes at the beginning of each chapter together with a comprehensive index at the back of the directory. Of the three directories reviewed, this is the most comprehensive, covering topics not covered elsewhere, e.g. transponder brokers, launch services, financial services, insurance, publishers and attorneys.

The listing of equipment suppliers is particularly comprehensive and the chapter on system operators has some good tables and figures that are difficult to come by.

R. Liu

## NOTES FOR CONTRIBUTORS

1. Manuscripts should be submitted in triplicate to Professor Barry Evans, Department of Electronic & Electrical Engineering, University of Surrey, Guildford, Surrey GY2 5XH, UK, or Dr Roger Colby, INTELSAT, Box 32, 3400 International Drive NW, Washington DC, 20008–3098, USA.

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2. H. L. Van Trees (Ed). *Satellite Communications,* IEEE Press Book, New York, 1979.
3. J. C. Fuenzulida, O. Shimbo and W. L. Cook, 'Time domain analysis of intermodulation effects caused by non-linear amplifiers', *COMSAT Tech. Rev.,* **3** (1), Spring 1973.

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